



PHD

An insight into the design process of unconventional structures

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AN INSIGHT
INTO THE DESIGN PROCESS
OF UNCONVENTIONAL STRUCTURES.

VOLUME I

Thesis submitted by Maria G. Voyatzaki
for the degree of PhD of the University of Bath.

1996

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ABSTRACT

This thesis studies the design process of unconventional structures starting with the hypotheses that it is different from and more difficult than that of conventional structures.

Nine unconventional structures provide case studies for the exploration of the design process. Interviews were carried out with architects and engineers who participated in the design of each case study. The interviews form a historical record of the views of leading designers, some of whom have dominated the field over the last thirty years.

The interviews show that difficulties lie in the nature of tasks and timing of the intervention of each discipline, in the specific knowledge of technical issues, in the degree of experience of individuals in the field of unconventional structures, in the different degree of familiarity that individuals have with means of communication and simulation and in the new architectural language of forms.

These conclusions were tested against further research based on a study of the literature describing three further case studies and interviews with four leading designers. The outcome of this work confirmed that the design process of conventional and unconventional structures is an intuitive, cyclic problem-solving task which involves the modification of preconceived models in order to arrive at a solution. This process functions and follows the same pattern of iteration and testing of ideas by error elimination irrespective of the conventional or unconventional nature of the outcome.

Thus the design process of conventional and unconventional structures is essentially the same, refuting the first hypothesis, but the design of unconventional structures involves a greater number of iterations to eradicate difficulties. In architecture tests are largely qualitative. In engineering they are more quantitative and when designing an unconventional structure it is necessary to invent not only the solution but also the test.

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PART I. INTRODUCTION AND LITERATURE REVIEW

Chapter 1. Introduction.

1.1. A brief history of the work.

Perhaps the best way to inform the reader of the contents of this thesis is to describe the process by which the work developed.

The original intention was to study the methods used by architects and engineers in the design of tent and cable net structures. Design involves the interaction of aesthetic, planning, structural, thermal, lighting, acoustic, materials, constructional, detailing and cost considerations. The architectural possibilities of tent and net structures can only be understood in relation to technical possibilities and problems.

Most research work in engineering is very detailed, technical and narrow with little attempt to take a holistic view of the decisions and compromises that have to be taken in the design process. This may be acceptable in the assembly of technical knowledge for the design of a jet airliner where engineers of different specialities work together. As engineers the members of the design team will share a common culture and the relative merits of two proposed design solutions can be assessed using objective criteria such as weight, fuel consumption and cost. Engineers rarely ask themselves philosophical or psychological questions about what they are doing, the intellectual effort of dealing with technical and management problems being enough to cope with.

There exists a large body of technical research into tent and net structures, but it is difficult to translate this knowledge into architectural possibilities. Technical constraints often work in opposite directions. Light weight is to be desired to span a long distance with structural efficiency, but mass is required for thermal inertia and acoustic separation. Even if it is possible to put objective costs to some of these criteria such as

cost of building and fuel costs, how can these be weighed against less tangible architectural considerations?

Somebody has to evaluate conflicting requirements and constraints in the design of a building and suggest a way forward. It is not necessary that this person be an expert in every aspect of architecture, structure, thermal performance and so on, but they must have sufficient knowledge to have a meaningful dialogue with specialists in each field. Usually the person charged with assessing the requirements and constraints will be a specialist in some field and it is perhaps most appropriate that this field be that which is most central to the success of the building. This would usually be an architect, except, perhaps, in the case of a largely technical building such as a factory.

Thus the original aim of the research was to assemble sufficient information about the technical issues related to the design of tent and net structures to enable an architect to have an understanding of the possibilities and problems of such structures and to have a meaningful dialogue with other specialists. Had this aim been achieved it would have established a vocabulary and grammar for the thesis to discuss unconventional structures which have been built and future possibilities.

In order to achieve this the researcher studied the methods of physical and computer modelling for the form finding and structural analysis of tents and nets. This was followed by studies of the thermal, acoustic and lighting performance of tent and net structures. This work is presented in chapters 2 and 3.

Michael Dickson of Buro Happold suggested that the researcher should conduct interviews with architects and engineers who had collaborated on the design of 'unconventional structures' – we shall return to the question of a definition of 'unconventional'. The aim of these interviews was to establish the ways in which architects and engineers integrate technical knowledge with the desire to produce buildings with a certain quality.

The researcher conducted two pilot interviews followed by interviews with seven architects and seven engineers who had collaborated on the design of seven unconventional buildings. The questions that were put to the architects and engineers were intended to be largely technical. This was not because it is considered that technical considerations are the only or the most important factors in design, but because technical competence is the foundation on which creativity rests. This work is presented in Part II of the thesis. In order to investigate further the research questions, three further building case studies were carried out. These case studies were performed via a literature review. Finally, four leading practitioners were interviewed. They were asked questions specifically aimed at testing the validity of the conclusions drawn from the nine building case studies.

The three further building case studies and the four further interviews are presented in Part III of the thesis, together with an overview and the conclusions.

It was tacitly, and with hindsight naively, assumed that the interviewees' answers to questions would be like pieces of a jigsaw and it would be simply a question of fitting the pieces together to get a 'picture' of the design process. It was realised that there would be some pieces missing and that sometimes the architect's and engineer's pieces would overlap, but nevertheless it was expected that some sort of picture would emerge as to how the technical issues related to the design of unconventional structures are resolved.

It soon became apparent that it was not going to be an easy task to establish patterns in the data from the interviews. This applied even to answers which were just questions of fact. It is unlikely that this problem was due to mendacity on the part of the interviewees, it was just that the interviewees had very different views of what had happened.

It is as if each interviewee constructed his or her own internal picture of the design process, then through their answers to questions each afforded the researcher a glimpse of part of the picture. The researcher then had the task of interpreting these scraps.

This raised all sorts of questions –questions of psychology, questions of methodology, questions of academic respectability. The original technical questions were not answered, at least not particularly satisfactorily, and all sorts of other questions were raised by the interviewees' statements.

By far the clearest picture that emerged was that of the human stress and conflict that occurred in the design process. In the design of 'conventional structures' architects and engineers know roughly what is expected of them, they ask each other certain questions and give answers, they feel reasonably confident about their technical ability. Inexperienced architects and engineers work alongside their older colleagues who can give them the benefit of their experience. There is still scope for conflict and stress, but at least they exist within a framework that is well understood.

Thus, as far as the individual architect or engineer is concerned, the use of the term 'unconventional structure' reflects to their own unfamiliarity with the design process of the type of structure on which they are working. They may not understand their role in relation to the other members of the design team, they may be unfamiliar with the technology of construction and with the technology of design, particularly computer programs used for analysis and the production of drawings, where conventional hand drawing techniques are inadequate for the description of complex curved objects. In addition individual architects or engineers may be in conflict with specialists whose fields overlap their own and they are torn between the desire to be innovative and the fear of failure.

It was stated that the interviewees' accounts raised more questions than they answered. On the face of it that might be considered to be some kind of failure, but the most

difficult problem in research is not to find the right answer, but to find the right question.

It would appear that here the question is not how to solve certain closed technological problems, but how to integrate architectural and engineering creativity with the rigorous study and thought necessary to allow for control over unfamiliar technology.

1.2. The problem.

Unconventional building structures use a combination of materials and forms which differ from the majority of contemporary buildings. A reinforced concrete frame would now be considered conventional, but this would not have been so at the turn of the century.

Long span structures covering column free spaces have acquired an increasingly crucial position in the vocabulary of architecture and engineering. With the need for large scale projects for industrial, transportation and leisure use, the number of these structures is set to increase even further.

From the designer's point of view, unconventional structures of this type represent a challenge for innovation and structural achievement, and from the client's point of view unconventional structures represent a major investment.

For a successful approach to the design of unconventional structures, there is a need for designers to have detailed knowledge of the technology as well as a proper understanding of design as a process. As far back as 1984, Goldsmith suggested that information is lacking in the literature, forcing designers to undergo a wasteful process of trial and error as they learn from their mistakes:

“there are two reasons for this: the lack of historical precedents to which an architect can refer and a new type of design process, which is both unfamiliar and potentially threatening” (Goldsmith 1984, p.152).

The lack of detailed technical knowledge necessary for the design process of unconventional structures within the broader fields of architecture and engineering remains a matter of much concern. Indeed some commentators (Dalland 1984; Lalvani 1984; Medlin 1984; Schierle 1986) have gone as far as to suggest that the field is still in its infancy.

Research on unconventional structures has been undertaken up until now by specialist workers who explore particular problems. For instance, computer scientists (Wakefield 1984, 1986; Barnes 1975, 1984, 1988, 1992; Gruendig 1986; Gruendig, Linkwitz, Bahndorf and Stroebel 1975) have produced computer programs on form-finding techniques and visualisation of form. Material scientists (Pelissier 1962; Ansell 1984; Lehnert 1992) have discovered and tested the properties and potential of new materials suitable for particular building types. Acoustic (Holden 1984), lighting (Wilkinson 1984; Scheuermann 1991) and fire protection (Day 1984; Wilson 1984) studies have been undertaken by experts. Mathematicians and structural engineers (Williams 1984, 1990, 1992; Kulbach and Olger 1986; Haider, Strutt and Shier 1975; Semenetz 1986; Gibson 1988) have studied problems of design and analysis. Wind loading specialists (Lawson 1992; Cook 1984) have performed wind tunnel tests to find the effect of wind upon unconventional structures. Frei Otto and the Institute of Lightweight Structures at the University of Stuttgart (IL, SFB series) have carried out extensive research into the architectural and technical possibilities of lightweight structures.

It is essential to adopt a systematic approach together with an observation of the design process of unconventional structures in order to bring together these diverse areas of knowledge.

Technical information is dispersed in numerous academic journals and conference proceedings and is often written in language which can only be understood by people who are themselves already specialists.

The present study was carried out during a period which was significant for the design of unconventional structures. Although the concept of “lightweight structure” is not a new one (the Dome of Santa Maria del Fiore by Brunelleschi (1421) can be considered to be a lightweight structure due to its small thickness/span ratio), the use of the term “lightweight” structure is relatively recent and stems largely from the translation of *leichte Flächentragwerke* (literally ‘light surface bearing structures’) used by Professor Frei Otto. It has been used only for the past forty years to describe buildings providing long span column-free space by employing the least possible material. Bobrowski (1985) argues that the structural achievements of the last two millenia have been related to the “dramatic decrease in the ratio of weight per unit covered area” (p. 13).

After a period of development, we are presently living on the borderline between the pioneers who contributed to and gained their experiences from the design of early lightweight structures on the one side, and the next generation of designers of unconventional structures on the other. The pioneers include Frei Otto, Ted Happold, Felix Candela and Peter Rice. The younger generation can benefit by learning from the knowledge acquired by the pioneers.

Overall, the published literature has been incomplete in many aspects. A wide number of factors still need to be explored in a more concrete way. There is a need for detailed research on the processes and practices that designers employ when designing unconventional structures. Thus, there is a need to tackle the research gaps and advance the literature if teams are to handle the design of unconventional structures with some degree of proficiency.

1.3. The aim of the study.

With these deficiencies in mind, the central aim of the current research is to explore and give an insight into the design process of unconventional structures. It is hoped that the results of the present study will be used to enrich the educational background of

architects and engineers, and inform designers about obstacles, constraints and new techniques involved in the design process of unconventional structures.

1.4. An analogy.

In any artistic creation, what comes to distinguish individuals and their artifacts from others are unique interpretations, imagination and skills as well as knowledge gained from experience (Broadbent 1973; Lawson 1980). The variety of interpretations derives from the influence of the cultural background on the way individuals perceive different stimuli. Imagination together with acquired knowledge and skills are all necessary elements in creating a composition.

In group work there is a sequence of individual tasks that must be followed, in order for the final outcome to be successful. In music, after the composer composes a piece, he or she may then execute the piece himself or herself along with other musicians in the orchestra. At other times a conductor may conduct an orchestra so as to perform the “same” piece of music. Several versions of the same piece may appear as a result of different individual interpretations.

In contrast to strictly structured classical music, the composition and performance of jazz has a great degree of freedom in improvisation and expression. It can be similarly argued that designers of unconventional structures add onto their basic knowledge in an improvising manner. However, there is still skeleton or structure in the composition of improvised jazz. As Berendt (1976) explains, “the jazz musician improvises on a given harmonic structure that is exactly what Johann Sebastian Bach and his sons did when playing a chaconne or an air: they improvised on the harmonies on which the melody was based, or embellish the given melody” (p. 125).

There are many similarities between music and design, but there are differences too. For example, Archer (1964) does not see the composition of music as design, “due to lack of the embodiment of the design as an artifact” (p. 4). According to his view, the

word “creation” is more appropriate than “design” when there is no representational model intervening between the concept and its execution. An architect’s drawing or physical model is representational but a musical score is not.

In general, the designers of a building conceive the form and then the way to construct and manufacture it. When the design team works with conventional techniques, the design process has a strict structure and “existing rules of usage” (Happold et al. 1976). Each of its members has a specific task and involvement in the design. However, following the analogy of music, if a design team “improvised” on a design process which was based on a skeleton, the resultant building could be “innovative”. This is not to suggest that innovation also follows from improvisation.

Innovation in architecture is often an end in itself, but it should be well-founded and well-justified to break away from the norm.

Communication during the design process of unconventional structures is more difficult than during that of conventional structures due to the novelty of the ideas and the lack of established norms in the design process. Addis (1992) argues that only with a language of criticism can discussions on the results of the engineer’s creativity and aesthetic judgements take place.

It is most common or even “inevitable” that when unconventional structures are designed, their innovation will breed disagreements as something new and unexplored. These disagreements can be useful but must be sorted out before they become destructive (Happold et al. 1976).

It should be noted that the term “innovative”, which has been associated with the term “unconventional”, is a relative term depending on time and location. What was considered “innovative” a few years ago might not be so any more. As far as location is concerned, a building type that is seen as “innovative” by the inhabitants of one country may be seen as conventional by the inhabitants of another; for instance, a tent is viewed

as an innovative building type in western culture, and as a classical building type in Arabic culture.

1.5. The area of the study.

Throughout the history of architecture innovative designers making significant advances have been attacked by “experts” and the general public. During the Renaissance, Brunelleschi’s audacious desire to go further than Nature and give the dome of Santa Maria del Fiore (1421) a slimmer span/thickness ratio than that of the egg, was vigorously challenged by the established authorities (Parsons 1968).

Such misunderstandings and mistrust can be a drawback when innovation is introduced. In the story of the Tower of Babel, God punished humans for their attempt to reach Heaven by preventing communications between them (Genesis 11: 2-9). This lack of a common language made it impossible for men to continue building the Tower. In order to exchange ideas a common language is necessary and becomes more important especially when the ideas are complicated and/or innovative.

Whitby (1985) attributes this unhealthy tension between the disciplines to the differences in the process of educating architects and engineers. Moreover misunderstandings exist not only between people of different professions but also between people of the same profession.

Although disagreements can sometimes lead to useful and constructive discussions in the decision-making process, they are often destructive. Further, disagreements are more likely to appear in innovative designs which do not employ conventional techniques. Of course, there is always the danger of the opposite extreme where individuals fail to express their views. That could suppress “good” ideas and give a false sense of consensus (Baron et al. 1992).

Although many innovations have often been completed successfully, a substantial number of them have not. In many cases, disputes, misunderstandings and lack of

knowledge have led to overdesigned structures and to failures. The failure may be architectural or in the thermal or acoustic environment or in the durability of the fabric of the building. The failure may even be total collapse.

The unconventional structures that will be examined in this study are long-span structures covering column-free spaces without employing beam-column structural systems. Such unconventional structures are characterized by their “structural honesty” and economy in the use of material (Addis 1992). For this honesty to be achieved form must coincide with structure. That means that the design of the one cannot be considered in isolation from the other. Architects must understand the structural behaviour and engineers must be aware of the manner in which the structure influences the architectural form. The line of demarcation between architects’ and engineers’ duties and tasks is blurred.

1.6. The research questions.

The research questions this thesis sets out to answer are:

Research question 1: Are there differences between the design process of unconventional structures and the design process of conventional structures? If so, to what are these differences attributed?

Research question 2: What are the difficulties that make the design process of unconventional structures more problematic than the design process of conventional structures? To what are these difficulties attributed? The adjective ‘problematic’ is here used in the sense of ‘difficult of solution’ or ‘not certain to happen’.

These research questions are aimed at confirming or refuting the hypotheses that the design process of unconventional structures is different from and more difficult than that of conventional structures.

1.7. Methodology.

In order to answer the research questions, case studies on the design process of nine unconventional structures were carried out. Architects and engineers who worked on the projects were interviewed and the resulting information was analysed using the method of Grounded Theory to produce a Paradigm Model. The terms “Grounded Theory” and “Paradigm Model” will be discussed in chapter 4.

In order for the findings drawn from the nine case studies to be validated externally, another three case studies of unconventional structures were carried out. Information was drawn from documentation for these three case studies for which, no interviews were conducted. Finally, further interviews were carried out with two architects and two engineers. They were asked specific questions relating to the conclusions drawn from the nine major building case studies. The interview transcripts were not analysed using the Grounded Theory because the Grounded Theory is aimed at establishing the issues and these had already been defined in the nine case studies.

1.8. A note on terminology.

This section attempts to define certain terms used in the study. Firstly we shall return yet again to the question of what the ambiguous term “unconventional structure” should be taken to mean. Unconventional structures may be seen differently by individuals belonging to different disciplines. This confusion tends to lead to further communication problems.

More specifically, design engineers, the general public and finally “the engineers working without the architect” (Holgate 1986) define the term unconventional differently.

i. For design engineers, unconventional structures are those which are:

“a) relatively novel (e.g. space frames, membrane roofs, inflated structures, cable structures and shells)

b) relatively rare structures” (ibid)

ii. For the general public, unconventional structures are those which are

“a) unfamiliar because access is difficult or restricted...

b) structures–‘intruders’ either in the natural landscape or in the built environment.” (ibid) and

iii. For engineers working alone, unconventional structures are those which:

“stand outside of the traditional scope of architectural (*sic*) theory.” (ibid, p. 1)

One way in which unconventional structures can be defined is by a process of elimination. By analyzing the structural action of a design, and comparing it with that of a number of types of conventional structure, structural types possessing an unconventional nature can be singled out .

Dickson (1992), for example, argues that:

“conventionally, building structures are frameworks of beams and columns, stable walls and floor plates, stiffened and joined to provide a three-dimensional continuum. Occasionally, however, a structure will evolve in which, by virtue of its form, significant bending stresses are confined to particular regions (or are insignificant). Loads can then be carried either in direct compression, as in an arch, or in tension, as a cable or membrane, or in a combination of direct forces and shears as a shell.”

(cited in Addis, 1992).

In the literature, there are terms such as “High-Tech”, “lightweight”, “tension”, “tensile”, “tensegrity”, and others which describe structures which have characteristics

in common with each other. Nevertheless, the terms are not well defined and therefore there is confusion due to the contradictions and inconsistencies that arise.

One of the terms which is often associated with unconventional structure is that of “High-Tech”. This is a term used to describe a fashionable architectural style of the 1980’s which faded with the same fast rhythm with which it had spread and had become popular. It is perhaps a coincidence that several notable High-Tech buildings made use of unconventional structures, for example the Schlumberger Research Centre in Cambridge. Davies (1988) gives a broad term of “High-Tech” relating it to the materials employed and the way they are connected:

“the physical and ideological features of High-Tech are analysed as its characteristic materials are metal and glass, that it purports to adhere to a strict code of honesty of expression, that it usually embodies ideas about industrial production, that it uses industries other than the building industry as sources both of technology and of imagery, and that it puts a high priority on flexibility of use” (p. 5).

According to this definition, the one common thing shared by unconventional structures and High-Tech is the pursuit of the Modernist ideal of honesty of structural expression. However, Eekhout (1988) has challenged the term “High-Tech” by explaining that it has been invented by architectural critics merely to point out the architects’ showmanship. Instead of expressing the structure in an honest fashion, High-Tech buildings often emphasize their structures by overdesign.

Another popular term associated with unconventional structures is “lightweight structures”. Henicke (1988) has defined as lightweight the objects which are capable of transmitting the forces with a small mass. And he adds that:

“Lightweight structures are the result of optimization processes which, for one reason or another follow the principle of a reduction in mass and/or

energy without a loss of efficiency. This is the principle of lightweight structures.” (p. 277).

Cowel et al. (1983) from the lightweight structures group of Ove Arup and Partners have given another definition to the term “lightweight”:

“lightweight structures are a group of flexible surface structures in which curved prestressed membranes made from modern industrial fibres are combined with cable systems or compression networks. Intriguingly, these surfaces act simultaneously as structure and as space-enclosing/climate modifying skins.” (p. 28).

The above definition is debatable and contradicts that by Henicke. It can be argued that, domes and vaults are “objects” which transmit forces with a “small” mass. The lightweight concept stands on the ratio of span to thickness. “Lightweight” as a term to describe structures is a relatively flexible and broad one. Technology and material industry are continuously advancing so that a building which was considered “lightweight” some years ago, may nowadays fall into a category of “heavier” structures. The reason is that, compared to other lightweight structures, modern ones employ less material and more advanced technology to cover the same span. Therefore any classification of a building as “lightweight” is debatable. For instance, the domes of Santa Maria del Fiore (Trachtenberg 1983) and Hagia Sophia (Joedicke 1985; Mainstone 1990) may be defined as lightweight in their concept, despite their thickness and dead weight.

The term “lightweight” has been connected with tensile structures. This association, according to Addis (a, 1992), can be interpreted structurally since tension is “the most efficient way to use a material”. Happold (1989) explains the relationship between “tension” and “least weight”:

“Achieving structures of least weight is such an approach-development of tension structures is the result.[...] a surface stressed structure aims to achieve a minimum increase in force level, and thus minimum need for expensive material, by distributing loading by an acceptable change of shape” (p 2).

Thornton (1992) has also defined a structure as “tension” where ties –members exclusively designed to carry tension– are the major elements. In the design of members that may be subject to both tension and compression, the allowable stresses are often reduced to prevent buckling, whereas members that undergo tension only work to the full tensile strength of the material. In buildings, tension structures fall into two groups: cable stayed structures and fabric or net structures. The masts of a tension structure are in compression and are a major element of the structure. For air-supported structures the internal pressurised air forms the compression element.

Lalvani (1984) states that:

“[Tension structures] are ‘curved space structures’ and part of the broad generic category of ‘space structures’. Curved structures are characterized by curved elements and are thus easily distinguished from other space structures like space frames, and constructions which use columns, beams, panels and slabs; all of which commonly use straight and flat elements.” (p. 142).

Pugh (1975) defines a tensegrity structure as a system in which “the components under compression do not touch one another, the structural continuity being achieved through a continuous network of tensile components” (p. 707). Comparing this definition to that of Thornton’s on tension structures, it appears that a tensegrity structure represents a special form of tension structure.

Although tension structures are often seen as innovative long-span structural solutions, the idea itself is not a novel one. As Boys (1963) has stated the idea of tension structures has been around for many centuries:

“its [tent structure’s] use –of tension– goes back behind the grass rope span across Tibetan gorges to some of the earliest human shelters slung between trees. Steel suspension bridges were some of the proudest and most spectacular exhibits which the engineering profession produced.” (p. 330).

Earlier on unconventional structures were associated with innovation. According to Rogers (1986) “innovation” is a subjective word with its meaning varying amongst individuals:

“The perceived newness of the idea for the individual determines his or her reaction to it. If the idea seems new to the individual, it is an innovation. Newness in an innovation need not just involve new knowledge.....The ‘newness’ aspect of innovation may be expressed in terms of knowledge, persuasion, or a decision to adopt.” (p. 186).

Liddell (mimeo) uses the term long-span and describes the relationship between tensile and long-span structures: “Full advantage can be taken of high strength materials –that can carry only tension– to create light, efficient and cost effective long span structures.” (p.2). The question is how “long”, a long span should be to be labelled as such, and also whether there are any limits as far as a length is concerned.

According to Berger (1985), “fabric tension structures are at the same time structure and envelope, building sculpture and architectural space, lighting system and acoustical environment” (p. 152). These are characteristics that can well refer to a thin concrete shell or a glass house.

Lastly, the structural term “surface structures” is used, though not widely, to describe a curved surface which carries loads primarily by tension and compression in the plane of its surface (a surface is an object whose third dimension is significantly smaller than the other two (Joedicke 1963)).

The present study employs the term “unconventional” which is broad in order to avoid confusion and to cover the whole area, including most of the above mentioned terms. Contradictions and overlapping are common when structures are to be classified or defined.

1.9. Organisation of the thesis.

It is probably true to say that most theses follow a roughly chronological order. A question is posed, other workers’ contributions are discussed in the literature review, theories and hypotheses are put forward, the collection of data is described, the theories and hypotheses are tested against the data, conclusions are drawn. Even if the research itself didn’t follow this idealised model, this fact is not alluded to in the thesis. There will always be some iteration, a theory is tested, found wanting in some way, a new or revised theory put forward and so on. This is to be encouraged, it is the foundation of the scientific method.

The problem encountered with the work to be described in this thesis is that the data collected from the interviews lead not so much to answers to questions as to a revision of the questions that should be asked. In other words, the iterative loop is not just within a relatively small central part of the thesis, but goes right back to the start.

The author decided to follow the chronological approach. Thus the original literature review, questions and methodology are first described. This is followed by a re-evaluation of the questions and methodology in the latter parts of the thesis.

The thesis is organised into three parts:

Part I contains the present introductory chapter, plus two chapters of literature review. In chapter 2 there is an introduction to the architectural and engineering aspects of unconventional structures. Chapter 3 is a historical review of the design process. A first attempt to understand what differentiates the design process of unconventional from conventional structures takes place. Documented difficulties are reviewed to illustrate the problematic nature of the design process of unconventional structures.

Part II describes the nine building case studies. A methodological framework is developed in chapter 4, following the review of some existing theoretical and empirical methods of recording the design process. The framework dictates that the present research is conducted in a number of phases. Within these phases there is variability in focus, research strategy, mode of analysing findings, purpose and questions to be answered. Chapter 5 and 6 present the actual methodological procedure. Chapter 5 ends with the conceptualization of a descriptive story about the central phenomenon of the study (explication of the story line) and chapter 6 ends with the arranging and rearranging of the categories in terms of the paradigm so that they can provide an analytic version of the story (completion of the story line). The term “story line” is used in the Grounded Theory.

Chapter 7 elaborates upon issues that appeared in the findings concerning Group Dynamics.

Part III describes three further building case studies and four further interviews. It also presents an overview and the conclusions.

The first part of chapter 8 explores the design process as an iterative and cyclic problem solving process. The second part is an exploration of three additional case studies of unconventional, but non-tensile structures. This is followed by an analysis of four further interviews, two with architects and two with engineers. Chapter 9 contains an overview and the conclusions.

Chapter 2. Architectural and technical issues in the design of unconventional structures.

2.1. Introduction.

Before discussing the design process of unconventional structures it is necessary to examine the architectural and technical issues involved. These issues provide a range of possibilities as well as problems to be solved.

2.2. Structural issues.

Horizontal plate structures, such as concrete slabs, carry vertical loads by bending moments and shear forces. Curved surface structures, such as reinforced concrete shells, carry loads primarily by tension and compression in the plane of their surface. Fabric and cable structures buckle in compression and so can only carry tension. Masonry cracks in tension and, therefore, can only carry compression (fig. 1).

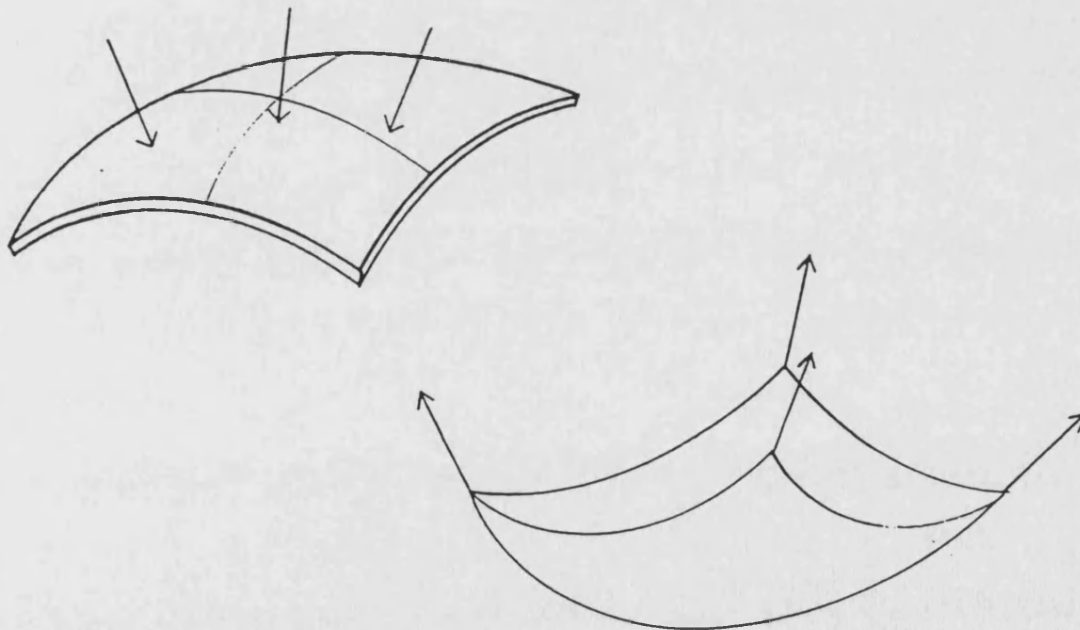


fig. 1: Shell in compression—fabric in tension.

The particular characteristic which distinguishes the design of surface structures from conventional structures is that their action depends upon their curvature and therefore

their overall shape. Thus the architectural design of such structures is strongly influenced by structural considerations.

Unconventional structures are characterised by “structural honesty” and directness because structure and form coincide.

It follows that members of the design team must appreciate equally well the concepts of “structural honesty” and aesthetics. In order for architectural and engineering aspects of the design to interact harmoniously, architects and engineers have to work together from day one of the design process (Hunt 1992; Barnes 1988; Happold et al. 1976). In the opinion of Hunt (1992) during “the design period of the project, an iterative process takes place such that, when the project is completed it is often difficult to know precisely who designed what” (cited in Addis, b, 1992, p.7).

Conventionally, a roof is a system of beams or trusses resting on posts or walls. In beams and trusses tension, compression and shear forces coexist within the elements that comprise the structure. When there is a need for a long span to be covered, the diameter or depth of elements must increase. In the design of conventional structures, highly stressed elements are made thicker to reduce stress. “Yet, in this process they attract greater loads and may consequently need further stiffening.” (Addis, a, 1992, p.13). Elements are characterised by their elastic stiffness which depends upon the material properties.

As spans increase, the stiffening or thickening of the elements that comprise a conventional structure can be aesthetically pleasing up to a point where the elements start looking inelegant. In a situation where a conventional solution generates problems of this nature, designers have to consider employing less conventional structural systems. These alternative structural types can cover a long span while minimising supporting elements by separating elements in tension from elements in compression.

The analytic techniques which explore these structural types were used by Gaudí in his “hanging models”. Forms generated from hanging chains were inverted to define arched and vault structures. Gaudí based his work on the assumption that when inverted the arches and vaults would be in pure compression (Tomlow 1986; Zerbst 1991).

The shape of a chain or a rope supported at its two ends is unique under particular sets of loads (Liddel, mimeo). It follows that geometry changes if the loads change (fig. 2) (Sandaker and Eggen 1993).

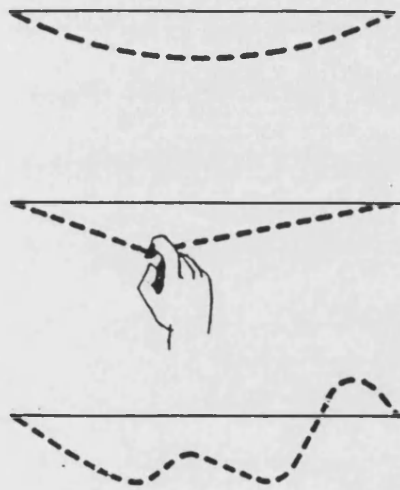


fig. 2. Rope under different loading conditions.

In conventional structures, stress changes and deflections are usually proportional to the imposed loads. That is the behaviour is linear. Thus, when loads double, stresses also double. The geometry of the structure may change due to loading but this change is small enough to be ignored (Thornton 1992). In contrast, unconventional structures, due to their changeable geometry, are usually non linear structures and the analytic techniques used do not follow those of conventional structures.

Due to their lightness, flexibility and change of geometry, unconventional structures are vulnerable to wind and snow loads. The low mass of unconventional structures makes them efficient in resisting the accelerations in an earthquake.

The resistance to wind and snow loads is one of the crucial factors that affects the final shape of a flexible structure. Wind loads, which often come in gusts, can cause dynamic loads the frequency of which should not coincide with the natural frequency of the structure (Sandaker and Egger 1993). Several ways have been devised to prevent buffeting and flutter, phenomena which may prove fatal for the structure. At the beginning of the development of tension structures, buffeting and flutter were handled by additional loads imposed on the flexible structure to counterbalance wind uplift (Buchholdt 1985). However, this method refuted the principle of lightness of the structure. An alternative method of stiffening tension structures is prestressing and the formation of 3D curvatures.

A flat membrane or straight cable under tension resists lateral load through geometric stiffness, that is stiffness which depends upon the geometry of the structure and the tension, not the material properties. In figure 3 the geometric stiffness is the lateral load divided by the deflection.

In figure 5 two cables are crossed and are prestressed so that one cable pulls up on the crossing point and one pulls down. When a load is applied to the crossing point, the stiffness is a combination of geometric stiffness and the elastic stiffness of the cables. If a large lateral load is applied one cable will go slack leading to a drop in stiffness.

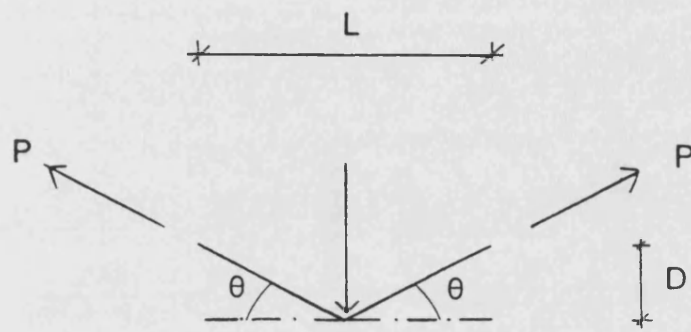


fig. 3. Relationship of geometric stiffness, lateral load and deflection. $F/D=4P/L$.

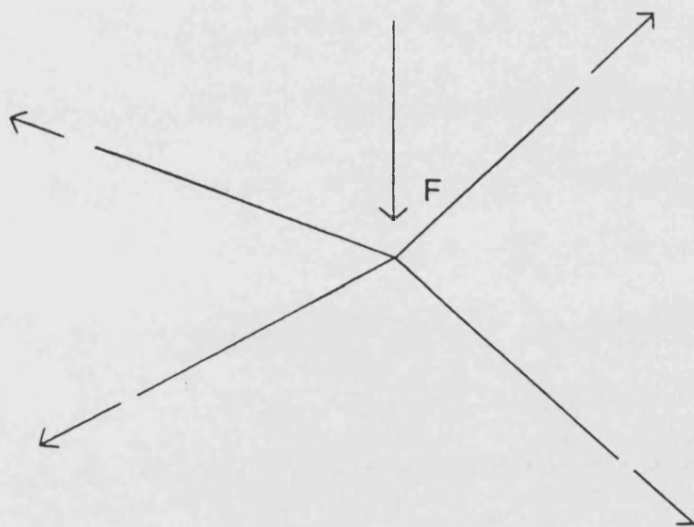


fig. 4. Large load applied to a cable.

A larger number of crossing cables can be prestressed to form a saddle shape as shown in figure 6. Again the stiffness is a combination of geometric and elastic. Thus the prestressing of a cable net has two functions:

1. to provide geometric stiffness
2. to prevent loss of tension in cables.

A fabric structure is very similar to a fine cable net. Again the prestressing is designed to produce geometric stiffness and to prevent loss of tension or “wrinkling”.

Due to their thinness, fabrics, cable nets and shells are two-dimensional load-carrying elements. They can be used to form single curvature surfaces like a cone, or a cylinder. When they form double curvature surfaces they can then be classified as:

- i) synclastic surfaces, which means that the centres of the principal radii are on the same side of the surface, or
- ii) anticlastic surfaces, which means that the centres of the principal radii are on opposite sides (Thornton 1992; Schierle 1986) (fig. 6).

Synclastic surfaces are ‘dome shaped’, while anticlastic surfaces are ‘saddle shaped’.

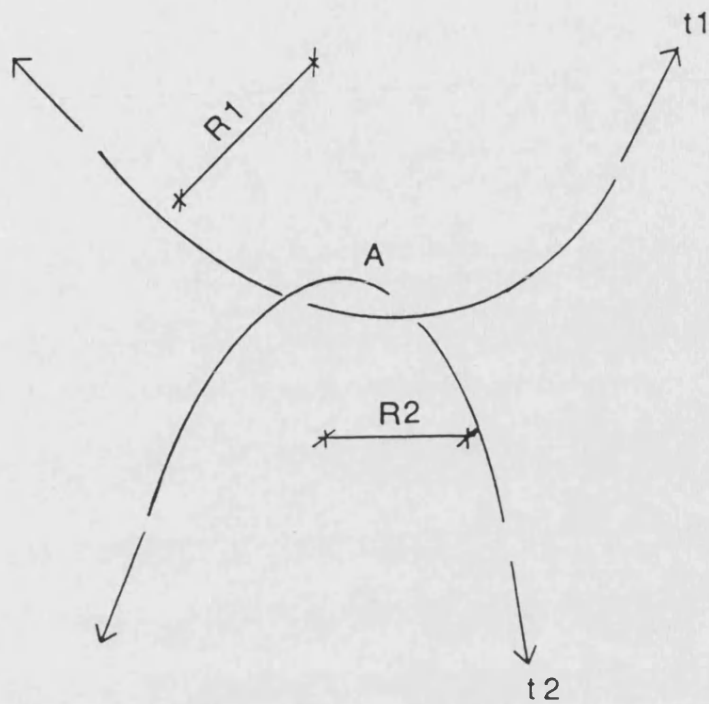


fig. 5. Two cables intersecting one another.

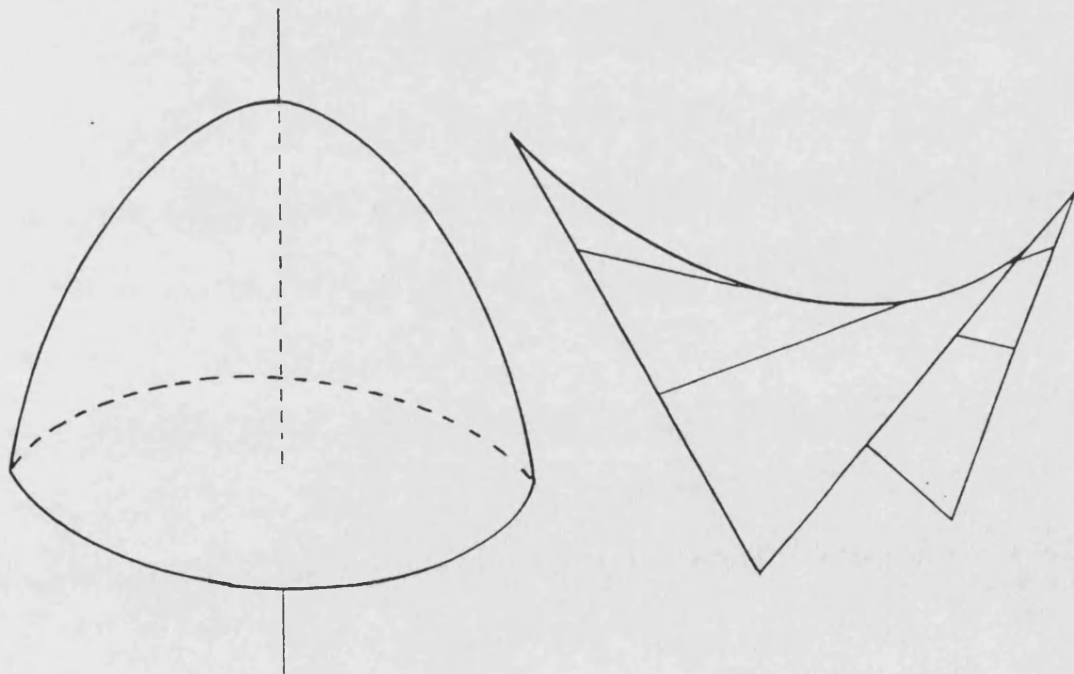


Fig. 6. Synclastic and anticlastic surfaces.

Classification of unconventional structures can be attempted according to the way in which a structure achieves stabilisation. Broadly speaking, a cable net functions as a set of ropes or cables hanging and meshing in opposite directions. A fabric, in turn, consists of individual threads tied closely, forming a mesh with a high amount of lateral stability. Traditional fabric structures tend to be relatively small span due to low fabric strength. They are formed by a small number of pieces of fabric seamed together. Nowadays, however, technological advances in materials science permit the use of materials like fibreglass cloth with a teflon coating for larger spans. Cable nets have further possibilities of covering a large space.

Before we attempt to explore the vocabulary of shapes it would be interesting to understand why concrete shells and thin vaults and arches are of importance to the purposes of this thesis. As Lalvani (1984) has explained, “tension structures have sometimes been compared to concrete shells in that they both have a structural basis for the development of form.” (p. 142). Similarly a grid shell has properties analogous to that of a flexible hanging net, that is if we assume that the interlacing cables of a net can be replaced by rods. Thus “a grid shell derives from the inversion of a flexible hanging net” (IL10 1974). The vocabulary of shapes that cable nets or membranes can form is enormous. The variation exists because of the supporting system and the boundary conditions which are defined as the rigid points, taking the loads out of a membrane structure or a cable net (Engel 1968; Otto 1954).

These types are then further classified according to the manner in which a structure is stabilised. A simple type of supporting structure consists of cables running along two or more rigid boundaries, defined simply as a suspended cable roof. The supporting structure can also consist of masts found inside or outside the structure, redirecting forces via ropes, cables or rods and transferring them to the ground. Convex, concave, and convex-concave beams running along the structure form another type of supporting system. Cable nets can also form grids, when they are double-layered or constitute multi-directional systems of intersecting cable beams. Apart from the simply suspended

cable type of structure, all the above mentioned solutions require a certain level of prestress or pretension (fig. 7).

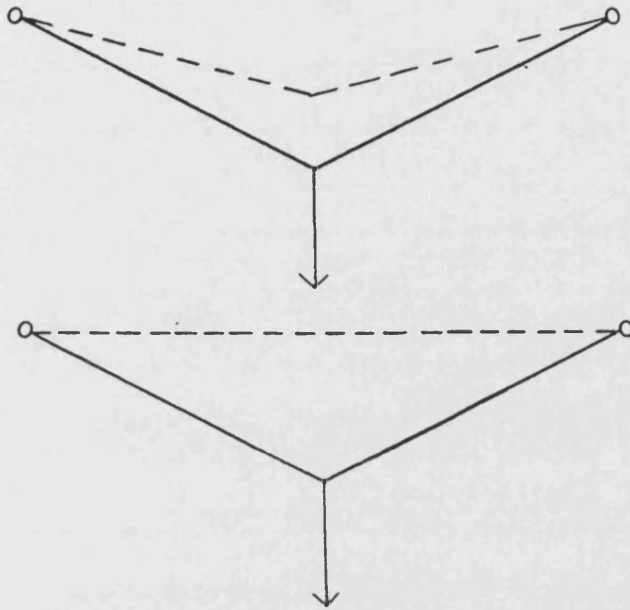


fig. 7. Prestressing a tie.

With regard to the boundaries, several types of members in compression can be used. Rings or any other shape of beams can be the edge of cable nets. Inner tension and outer compression rings can shape radial suspended cable roofs (fig. 8).

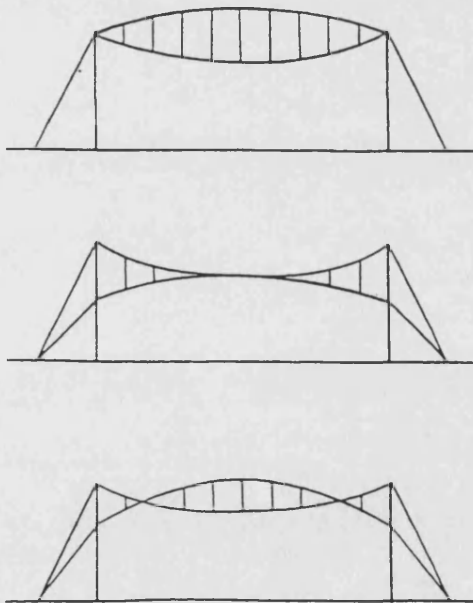


fig. 8. Convex-concave beams.

The variation of types regarding membranes is even more complicated (Thornton 1992). Again, supporting structures and boundaries –either hidden or exposed–

determine the appearance of a membrane. The simplest type is the hyperbolic paraboloid (a saddle shape). The ridges and valleys, which are the strong features of this basic type, can create numerous options. Lastly, another type of membrane structure, the air supported structure, uses air pressure to maintain the form of the membrane. The pressure is maintained by fans and the building is entered via air-locks or revolving doors.

2.2.1. Form finding and computer simulation.

Although an overview allows for classification of either cable nets or membranes into categories, the brief of each individual project can stimulate the designer to create a genuine building. Nevertheless, the characteristics of any curvilinear structure brings architect and engineer together in order to define the final shape and the devices which the structure will employ so that it will function efficiently in conditions of wind and snow loads.

At the conceptual stage, simple hand calculations can often provide sufficient information regarding stresses and deflections. Later in the design process, accurate numerical information is usually obtained from a computer analysis. The analysis has two phases, firstly 'form-finding' which defines the geometry of the structure and secondly analysis under imposed loads such as snow and wind.

Both the 'form-finding' and the analysis under load consider the equilibrium of applied loads and internal stresses on the one hand, and the compatibility of deflections and internal strains on the other. Thus, the same computer program can often be used for both functions.

Computer simulation is often based on the method of dynamic relaxation (Day 1965), conceived by Alistair Day of Ove Arup and Partners. The method is based on the fact that a structure moves in order to get from one state of equilibrium to another when loads are applied. Day wrote the equations of motion using this principle. The designer

can predict the gradual movements of the structure at any instant between different states of equilibrium (Barnes 1988).

Once a satisfactory shape or form has been found, it is necessary to produce cutting patterns for fabrication. This process has been defined by Linkwitz (1972) as the determination of the lengths of a structure's cables or of the shaping and dimensions of the fabric patterns comprising a membrane surface.

A computer can simulate the effect of the loading conditions and determine the cutting patterns. The role of an architect at this point is to ensure that convergence between the original concept and the computer outcome is achieved. Inaccurate specification of original geometry or boundary changes during form-finding could cause high load residuals (Barnes 1988).

2.2.2. Wind loading.

Often it is the dynamic nature of the loading which causes problems. Buffeting is dynamic load due to fluctuations in wind speed. These fluctuations are due to vortices carried along with the wind. The vortices are generated upwind of the structure and as the wind passes over the structure itself. Failure of the Ferry Bridge cooling towers was due to buffeting. Flutter is a dynamic load caused by the interaction of the wind and the movement of the structure. It can take place even in a steady wind and examples include the flutter of flags, leaves, Venetian blinds as well as aircraft wings and suspension bridges –the failure of the Tacoma Narrows bridge is a classic example.

The wind load on a structure is dependent upon its shape. If a load or force is proportional to a displacement it produces a stiffness like term which may be positive or negative. This is analogous to the positive geometric stiffness in a tension member or negative geometric stiffness in a compression member. Negative geometric stiffness can cause a structure to become unstable or buckle and similarly negative stiffness due

to air flow can cause instability. This instability is known as divergence. The classic example is the failure of the Fokker monoplane wings during the First World War.

Flutter and divergence are aeroelastic phenomena in that there is interaction of aerodynamics and elastic behaviour (Fung 1945).

When a fabric or net structure moves about in the wind, it is often difficult to distinguish the effects of buffeting, flutter and divergence. The movement of a fabric or net structure can be explored in terms of waves travelling across a structure. Divergence then occurs when a wave becomes stationary.

In April 1986, the Metrodome Stadium, an air-supported structure in the USA was hit by winds during a baseball game attended by 26 000 people. The incident was not fatal but was nevertheless destructive; the game had to stop for a period of approximately ten minutes, during which time the roof oscillated till it stabilized itself and allowed the play to resume (Maki 1992). It is obvious that flexible structures are more vulnerable to wind loading. It is probable that the movement of the roof was more a manifestation of lack of static stiffness, that is divergence, than flutter or buffeting (Williams, private communication).

Cook (1992) remarks that sensitivity to dynamic excitation is taken as a function of a building's height and type. Size can be another factor that affects the stability of a structure. Cook also stresses that larger airhouses are more susceptible to dynamic excitation as stiffness and damping is reduced due to end effects. Airhouses with more steeply rising forms are susceptible to buffeting and deflect with greater amplitude (ibid).

Lawson (1992) also supports the view that correct design can contribute to the performance of a flexible structure.

Structures which are not streamlined cannot be analysed using the classical methods of aeroelasticity. Designers have attempted to solve the problem empirically. To give a

rather old example, that of the Raleigh Arena, in North Carolina, the original design was not executed because the structure would have been inefficient in terms of resisting flutter (Fung 1945). Guide wires with adjustable springs had to be added. In the case of the Tacoma Narrows Bridge failure, it is believed that the structural type chosen played an important role. This is probably the reason why the Second Tacoma Narrows Bridge was designed “with open trusses as the stiffening members (instead of plate girders), open trussed floor beams (instead of solid) and streamlined tail sections”(ibid). Vibrational problems are discussed by Fung who suggests two possible ways to solve problems:

- the stiffening of the structure, so that the natural frequency is shorter than the frequency of the vortex shedding in wind, or
- the introduction of vibration dampers into the system so as to absorb the energy.

In their paper Severud and Corbeletti (1956) describe several ways of achieving stabilization of a flexible structure. For instance, inclination of the mast of a structure is one way of doing it. Symmetrical or asymmetrical saddle shapes with anchored perimeter and ends also provide inherent stability. Otto (1954) devoted a great part of his doctoral thesis to a discussion of the importance of the shape of anchorages to the stabilization of a structure. Connecting flexible structures to rigid buildings has been proven beneficial. In the Great Arch, in la Defense (Paris, 1989) and in Imagination Headquarters (London, 1987) the tents suffer little from destabilization caused by wind loading, because they are surrounded by rigid structures.

Lawson (1992) has added that, in order for internal pressure and wind loading to cooperate, the designer needs to take into account the relation of the internal pressure to the openings in the skin of a building.

There are many ways of simulating wind loads. The stability of a form can be assessed qualitatively by simple flexible wind tunnel models (Barnes 1992). Flexible or

aeroelastic models are designed to deform in the wind tunnel in the same way as does a real structure in a wind. On the other hand, rigid model tests are unreliable for predicting whether a structure is going to remain stable under wind loading.

Williams (1992) has stressed that erroneous results can be produced by a computer analysis following a rigid model with tunnel test. The importance of the accurate prediction of the behaviour of a flexible structure may make the wind tunnel testing of a flexible model a necessity. During wind tunnel tests, stiffness, mass and damping properties of the structure are scaled in order to predict actual deflections from the model itself (ibid).

2.3. Architectural considerations.

“The limitations of the tension structure discipline and the inherent structural expressiveness of the genre may seem unduly restrictive to an architect exploring their use for the first time.” (Huntington 1984, p. 138).

The quality of the work of the architect seems to depend upon his or her familiarity with tension as a structural concept within an unconventional context separated from compression. Designers have expressed the need for the development of a new architectural vocabulary. More specifically, Boys (1963) wrote that the architect who wants to “be able to design successfully in tension, should understand at least the behaviour of tension, if only to know when to call the engineer. And no less urgently he should understand the visual qualities of tension character, which is a sort of negative version of compression character” (p. 334). Elaborating on this idea, Goldsmith (1984) pointed out that “first architects must learn the rules for design of these structures and second they must be given the references by which they can accept the rules and create their own design vocabulary” (p.151).

It has been claimed that the lack of historical precedents is a source of problems for architects. Unconventional structures do not have precedent buildings but borrow concepts from two sources: technology applied to flying machines, kites, bridges; and to Nature (Goldsmith 1985; Lalvani 1984; Happold and Liddel 1976).

Dalland (1984) and Goldsmith (1984) have argued that the architect is inefficient in responding to the design process of unconventional structures. They go on to explain that part of this inefficiency can be traced to the lack of familiarity with “non-rectangular, non-Cartesian” forms. This unfamiliarity cannot be overcome by employing conventional architectural devices. As Goldsmith (1984) has pointed out, “Since you cannot apply scale to a doubly curved surface with traditional means such as windows, decoration etc., the proportion of the surfaces, of ridges and of the valleys takes on a heightened importance. Where mullions and arches created the rhythm and scale of traditional large structures, issues such as panel widths, geometry of cutting patterns become tools for the architect to manipulate” (p. 154).

The roof acquires a predominant role in the design of unconventional structures. Often the entire concept is based on finding a genuine way of roofing a space. It is interesting to note that in some cases the roof develops on its way to the ground, and becomes the side wall of the building (Thornton 1992).

Adaptation of unconventional structures to the landscape or urban context.

The three dimensional nature of unconventional structures makes their adaptation to the landscape or urban context a special issue. A rural landscape, with its inherent curvilinearity may be quite adequate to incorporate a curvilinear structure as its natural continuation. It is more difficult for an urban context consisting of mostly rectilinear forms to “embrace” a curved form (Otto 1954; Thornton 1992; Plemsus 1984; Scheuermann 1991). Most applications of unconventional structures are detached, pavilion type buildings.

Plan arrangement.

The subdivision of a large rectilinear, tall space both vertically and horizontally can be easily handled since the conventionally trained architect can by and large tackle grid patterns and right angles (Preiser 1986). However, the situation is quite different when the organic shaped plan of a curvilinear structure has to be subdivided. Research has been undertaken in the Institute of Lightweight Structures in Stuttgart, engaging in observations of spider webs, wasp nests and bodies of polyzoa (Schaefer 1967). These observations provided feedback to designers concerning the way in which an organic shaped plan can be divided. Most examples of unconventional structures are free plan large spaces. However, when the need for smaller spaces appears, quite often division of space can lead to smaller spaces with disproportioned area-to-headroom relationship. The difficulty of dividing a large space into smaller units has been 'overcome' in many cases by adding the ancillary spaces to the main building, usually adopting a conventional structural form. The juxtaposition of the two structures is not always successful.

Expansion.

The potential for expansion that some unconventional structural types have is interesting. Such are buildings with repetitive bays or plans based on a grid pattern. In 1956, the Paper Mill by Pier Luigi Nervi (Architectural Forum 1964) and the Schlumberger Centre in 1987 appeared to have the potential to expand. However, some years after the completion of the unconventional part both expanded into conventional buildings. Aesthetically, this could be justified as an attempt to maintain the integrity of an organic form, conceived as one. From an economic point of view, it could be argued that it is uneconomical and difficult to determine the construction method for expanding an unconventional structure.

Function.

Designers seem to have opposite views regarding the possible functions of an unconventional structure. One school of thought suggest that “despite their free form possibilities for symbolic expression, unconventional structures suppress individuals to personalize a large space and therefore they can only be religious or political assembly type buildings” (Preisner 1986, p. 9). The other school of thought supports the idea that the freedom of form of unconventional structures makes them suitable for any building type (Goldsmith 1984). However, it can be argued that the structural advantages of unconventional structures in covering long spans imply that the scale of the proposal must be large to be meaningful. That means that the building cannot be small, hence not of any type.

Other technical issues.

The inherent “thinness” of unconventional structures means that special consideration has to be given to the environment within the structure:

- i. Thermal exchanges occur faster in unconventional than in conventional structures. As a result, extra heating or air conditioning may be required according to the climate. The energy usage has to be taken into account in order to judge the appropriateness of an unconventional proposition (Preisner 1986).
- ii. Frequently, membranes or porous materials can generate condensation.
- iii. The “thinness” and “expressiveness” of the structural qualities of an unconventional structure do not allow the structure to incorporate and accommodate the services. Thus, the service systems have to be elegant (Addis, c 1992).
- iv. Thinness is also the reason for a peculiar olfactory environment due to the odour transition that can be generated through the skin of the structure (Preisner 1986).

- v. The ambient light of unconventional structures is in many cases not easily controllable. The luminous environment is mainly a result of the translucency of the fabric and the diffusion of sunlight (Wilkinson 1984; Mark 1990; Scheuermann 1991).
- vi. The inherent curvilinearity and thinness of unconventional structures can impose harsh acoustic effects. Reverberation time and echo as well as disturbance of privacy are the aspects the designer should consider when noise control is an issue (Preiser 1986).
- vii. Other technical issues include the fire resistance of the structure and the means of escape (Day and Green 1984).

2.4. Summary.

In this chapter, in a first attempt to answer the first research question –what are the differences between the design process of unconventional and that of conventional structures– it was indicated that the principles of the structural action of unconventional structures are based on the employment of tension in an unconventional manner. If tension is the predominant concept, then it follows that components carrying tension are the predominant ones.

The interrelation and interdependence of form and structure –or rather the coincidence of form and structure– are the main characteristics of unconventional structures which differentiate them from conventional ones. Hence architectural and engineering considerations are also interrelated and interdependent. A consequence is that structural analysis has to occur at that preliminary stage, when the form is conceived. That implies that engineers, who are responsible for the analysis, and architects who are responsible for the form, have to cooperate from the beginning of the design process.

One of the engineering issues which differentiates unconventional structures from conventional, is the vulnerability of unconventional structures to wind and snow loads. The review of several studies showed that some forms are more prone to failure than

others. That again affects the decisions to be made on the adopted form. In order for safety to be ensured, special computer programs and other unconventional tests and techniques have to be employed.

Additional architectural considerations are the result of the “engineering-predominant” nature of these structures. Thus, adaptation of unconventional structures to the landscape or urban context, plan arrangement, expansion, function, and technical issues such as lighting, acoustics and thermal behaviour have to be tackled differently.

Chapter 3. The nature of the design process of unconventional structures.

3.1. The design process.

Advances in technology and increasing complexity increases the risk of making major mistakes in design (Asimow 1962; Fuhrmann 1991). In the sixties, when the problem became acute, efforts to understand the design process in order to keep it under control were intensified (Fuhrmann 1991).

Relatively recent reassessment and reviews of ways to model the design process occurred with the development of Computer Aided Design (Kalay 1987; Coyne et al. 1990). In order for researchers to be able to create computer models which could perform the task of design “in a fashion similar to its human counterpart” (p. 65), the cognitive mechanisms that designers employ had to be understood (Akin 1978).

Two general ways of understanding the design process were identified in the past. Akin (1978) has explained that the first is an experimental approach, which uses deductive tools to describe design, and the second is a more theoretical approach, which uses empirical and introspective knowledge. The experimental technique monitors and analyses the information structures, what Miller et al. (1960) call “plans and images”. The more theoretical one explores “stimulus-reaction patterns developed from the behaviourist view point” (i.e. Simon’s problem behaviour graph, 1972). This approach studies the behaviour of the architects in the process of designing buildings (Newell’s protocol analysis, 1970).

Various individuals have explored and defined the nature of the design process not only from an architectural (Broadbent 1973) but also from an engineering (Ove Arup 1966) point of view.

Generally the design process can be described as a network of cognitive mechanisms, like the following global model provided by Mackinder and Marvin (1982) and by Cross (1984):

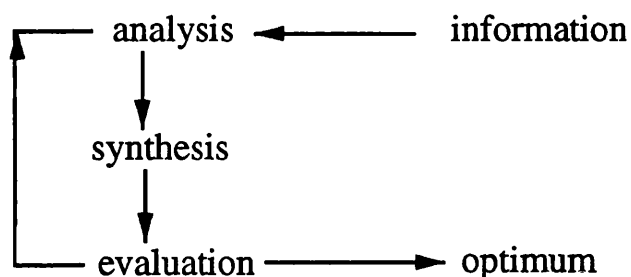


fig. 9. The Design Process. Institute of Advanced Architectural Studies. University of York, Jeremy Taylor. Source: Mackinder, M. and Marvin, H. (1982) .

In the model above, information received is offered from the brief usually imposed by the client and generally includes details on the budget available, the time limits and the use of the building. Sometimes the client may also express preference for a particular building type or material to be used. Other information given could range from environmental data regarding the site to the political and social context in which the project will develop.

Page (1963) defines the analysis-synthesis-evaluation stage as the appraisal of information according to the individuals' objectives.

Evaluation seems to vary according to the complexity of the design. Broadbent (1973) argues that "evaluation, traditionally, is a matter of experience and judgment but, as design becomes more complex, that becomes less effective" (p. 259).

The optimum is the most satisfactory outcome which has taken into account the information and has processed it through the analysis-synthesis-evaluation stages. Optimization as a mechanism, however, is the identification of potential designs for a given performance goal (Coyne et al. 1989).

Apart from exploring the cognitive mechanisms which designers employ during the design process, research has been undertaken regarding the nature and sequence in which these cognitive mechanisms operate. The RIBA Plan of Work defines the design process as a spiral one which is divided into four phases (fig. 10). It is argued that every member of the design team develops the same activity in each stage, but as the process goes on the activity is elaborated in more detail.

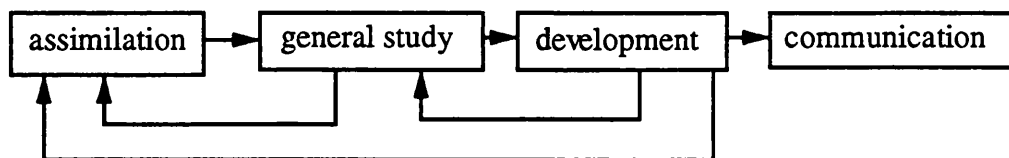


fig. 10. Activities taking place during the design process.

In other words, the tasks and objectives of the individual participants are clearly defined and after assimilating (“developing the combined solution through the modification of one to accommodate the other” Akin 1978, p. 78) and studying the variables of the given brief, individuals develop ideas and communicate them among themselves in order that a solution to the problem be found. The same process is repeated until the majority of objectives have been met.

Although some researchers have agreed that the design process in general is a cyclic one, Happold et al. (1976) have differentiated the design process of unconventional structures from the design process of conventional ones. They have argued that the design process of unconventional structures is a “stage-by-stage one”. According to the authors, there are four main stages of the design process. The contributors to each stage have different tasks and provide the design process with different information.

More specifically:

Stage	Contributors
1. Conception	Client and Architect
2. Selection of form	Architect and Engineer
3. Detail and Design	Engineer and Architect
4. Detailing, Fabrication and Erection	Contractor, Fabricator and Engineer

fig. 11: Stages and contributors to the design process of unconventional structures.

Source: Happold et al. 1976, p.431.

At the conception stage overall restraints and objectives are defined. At the selection of form stage, the architect and engineer discuss possible alternatives for the form of the building. The engineer's task is to explain the choices to the architect and "perceive and discuss the qualities desired by the architect". At the detail and design stage decisions on structural details are taken for the finalised overall concept of the building. At the detailing-fabrication-erection stage contractor, fabricator and engineer discuss the output of the third stage in order to establish the construction method to be adopted (Happold et al. 1976).

Addis (a, 1992) does not seem to agree that the design process of unconventional structures is a "stage-by-stage" one. On the contrary, he supports a model of the design process of unconventional structures similar to the RIBA Plan of Work which suggests that the design process is a series of cycles:

"The engineer is part of this cyclic process, sometimes contributing by saying what is or is not possible. This is particularly true of tension structures, whose precise shapes are utterly dependent upon the complex interrelation of stress, stiffness, stability and deformation in the structure." (p. 15)

The differentiation, according to Addis, lies in the engineer's involvement which, compared with conventional structures, is more dynamic and determining in the decision making. More specifically, Addis (1992) and Goldsmith (1984) have claimed that architect and engineer work together very closely during the whole process of developing the design of a building's structure from the early concept stage through to the level of fine detail and construction. Barnes (1988) also supports that "at a stage much earlier than is usual in the case of conventional structures, the engineer will be involved with the architect in the development of the design concept." (p. 327).

Researchers have attempted to define the nature of the design process of two unconventional projects considering its stages, the chronology and the actions taken, the participants and their tasks. In one project a group of architectural students in Delft (Netherlands) composed a flow diagram (fig. 12) of the design process of the Munich Olympic Roofs (Eekhout 1972, pp. 26-33). In another project Spaeh and Spring (1976, p. 59) published a flow diagram for the Mannheim Garden Centre (fig. 13).

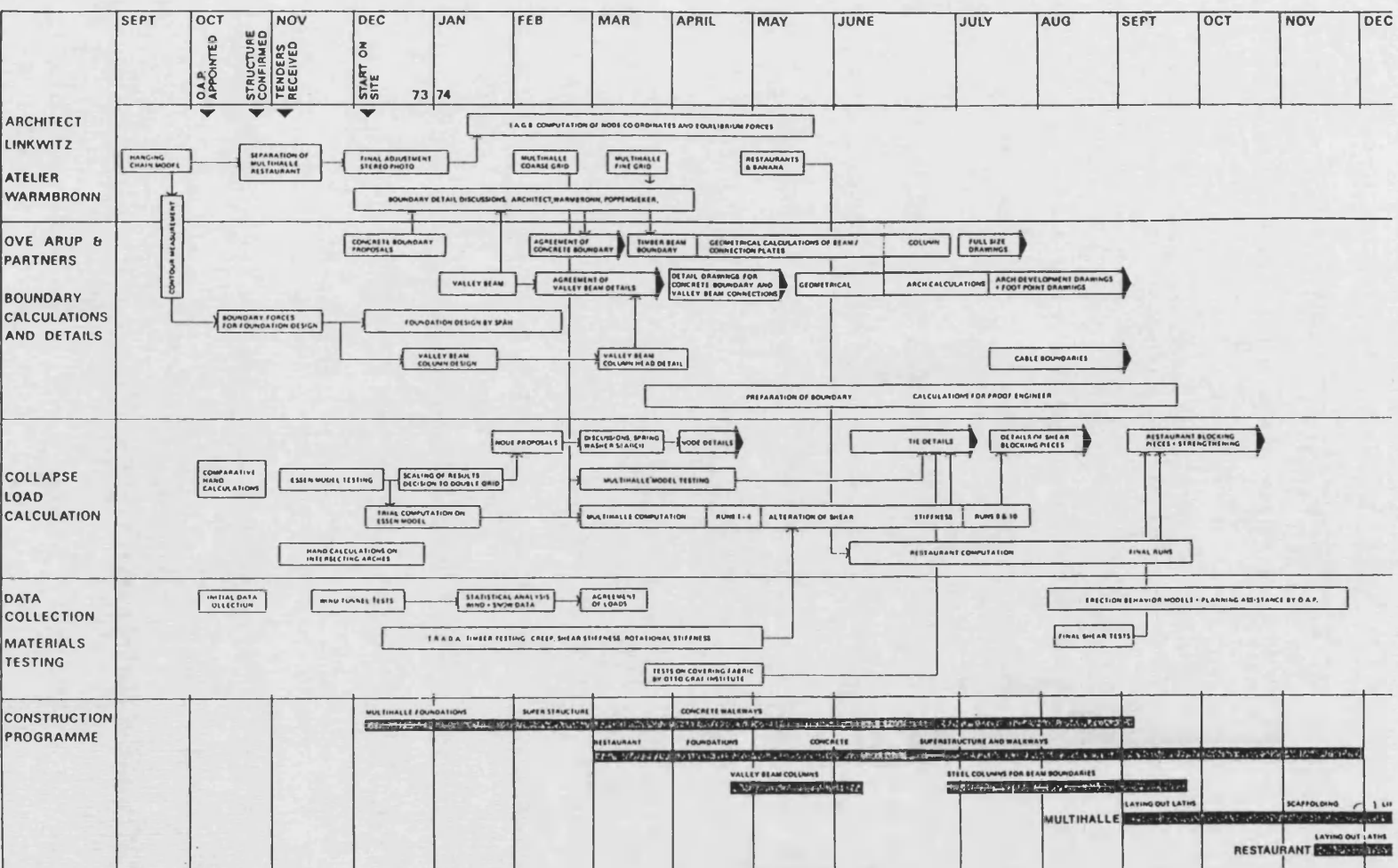


fig. 13. Part of the flow diagram for the Mannheim Garden Centre (Spaeh and Spring 1976, p. 59).

3.1.1. Historical background – the changing nature of the design process.

If the design process is to be seen as a problem-solving exercise which aims to find a solution to a particular problem, then it follows that the nature of the design process varies according to the nature of the problem that has to be solved. The design process of shelters or tools, for example, lacked skeleton and sequence of functions because, according to Cross (1986), it was an “unselfconscious” process, where the only prerequisite for its efficiency was craftsmanship.

Technological advances made in the use of materials are closely related to the evolution of the design process. Ackermann (1991) has argued that the change in material industry influenced the form, and has defined the result of this influence as “technological aesthetic”. Lawson (1980) has added to that the importance of the social and cultural influences on designers. Lawson has also argued that the design process is not an outcome of careful and conscious planning but is directly linked with the social and cultural changes. One example of that is the special building types that emerged due to the worship of political or religious figures. These building types had to be novel and impressive, as well as emblematic and imposing. Williams (1993) explains the practice of “building tall” as a matter of prestige. Another example that links symbolism of buildings to status is the medieval towers. These towers were to be seen as monuments the heights of which signalled the wealth of the patrons and merchants. According to Williams, the demand of building tall increased considerably during economic boom times (*ibid*).

In parallel with the economic progress necessary for the construction of these new building types was the necessity for building technology to explore new roof-covering techniques. Goldsmith (1984) explained that the key to the exploration of roof-covering techniques, from Gothic and Baroque churches to Art Nouveau and Expressionism, is the fact that buildings employ “a non-planar three dimensionality” (p. 151). Curvilinear

forms brought eccentricity and novelty to buildings with extraordinary uses, such as palaces and churches.

Although the new exploration of alternatives in building types enriched the architectural and engineering vocabulary, it also revealed numerous obstacles. For instance, although cathedrals expanded the limits of building techniques for more than four hundred years, the difficulties were many. This is evident from the fact that many of these buildings collapsed at some stage during their construction and the completion of many of them took over a century (ibid).

It would be interesting to look at the close relationship between the development of building materials and the form of structures. Masonry was the only material available when the architecture of vaults developed to cover long spans. In other words, the use of masonry in the construction of vaults implied heavy buildings which employed mainly compression (Torpiano, 1987). The development of light building materials advanced the use of new forms. The Industrial Revolution and the development of trade encouraged the exploration of new structural types. Long span bridges became necessary to ease the transportation of goods. Designers dealt with the bridge design, but also intended the new forms to act as representation of the new technological world. Robert Maillart (1872-1940), a Swiss engineer, gave bridge design an aesthetic dimension. While developing bridge design Maillart explored three major building types: the column-supported floor, the beam-supported roof, and the thin-shell vault (Billington, 1983).

In architectural structures, the height of buildings was of great concern. Unlike medieval cathedrals, the tall buildings emerging around 1880 in the USA did not aim to produce psychological submission of the masses. Their purpose was mainly to densify accommodation and transport, as well as to react against the increasing land values. The new technology of building skyscrapers developed rapidly once the structural problems were understood by architects and engineers. Other new building types such as

factories, exhibition centres, warehouses, market halls, aircraft hangars and sport centres also appeared. However, these new building types could adopt neither the newly appearing high-rise building technology nor the style of old traditional building types, which demanded the use of columns positioned in a dense grid. It was the exploration of bridge structures that influenced the development of long-span structures covering relatively column-free spaces. Further, this could be combined with the potential for expansion and lightness of the building (Ackermann 1991).

Prestressed concrete in the 1950's was a relatively new material that stimulated the interest of several designers of the twentieth century. Billington (1983) distinguishes three schools that dealt with curved concrete surfaces in terms of twentieth-century structural engineering, namely: the German with Dischinger and Finsterwalder as its main representatives; the Italian represented by Pier Luigi Nervi; and the Spanish with Gaudí (1852-1926), Torroja (1899-1961) and Candela (b.1910) as its main figures.

The German school is the least well known, because their works are not as beautiful as those of the Italian and Spanish school because of the visual thickness of the buildings. Nevertheless, the German school had a reputation for using mathematics to solve loading and other problems of form. Billington (1983) has given the following example: "Finsterwalder's first mathematical theory (technically called the membrane theory which considers the shell to have no resistance to bending) showed that unless the edge slope was purely vertical, the longitudinal edges of the barrel would need tangential supports" (p. 174). The contribution of the German school is the numerical exploration and the application of mathematics to the design of curved concrete surfaces.

The Italian school had influences from traditional masonry ribbed vaults. For instance, Nervi (1891-1979) developed ribbed concrete surfaces. As Eekhout (1988) has noted, the influences of Gothic cathedrals are obvious on Nervi's stress lines, and the way they flow from roof to column and down to the foundation. Nervi's concern about

aesthetics and architecture is evident in the articles he wrote such as: “The art and technique of building”, “Problems of architectural achievement”, “Technology and the new aesthetic direction” etc. However, means to test the safety and stability were not available at the time. This forced Nervi to test buildings during erection:

“While removing the scaffold, Nervi meticulously measured the deformations of the roof to check its safety and to learn more about the performance of his novel structure.” (Billington 1983, p 179).

The Spanish school’s main concern was the expression of thinness. Their explorations focused on the traditional vaulting form laid with laminated tiles. Gaudí attempted to depart from the tradition of the structure’s material and the determining power that had on the form of the structure. What is amazing and particularly interesting for the purpose of this study is the way in which Gaudí designed and tested his structures (Casunelles 1967). Following the principle that compression is a negative tension, he experimented with weighed chains. The shape of the chain arched by dead loads under tension would be in pure compression when inverted. Based on this principle Gaudí could achieve the desired form. Gaudí’s architecture as structures are admirable for their plasticity which are best captured by Calatrava’s description of them as sculptures that one can walk into (BBC 2, Building sights).

Torroja, influenced by Gaudí, attempted to search for similar forms in concrete. Felix Candela is the master of thin concrete shell technology:

“Candela had difficulties with some of his works from which he learned and improved. But his overall success as a designer came primarily from his central aesthetic motive and the recognition that proper predictions of thin-shell behaviour could only come from observations of full-scale structures in service.” (Billington 1983, p. 191).

Not only is Candela an architect, an engineer and a builder but, according to Billington, he is also a skilled mathematician. He produces innovation of design step by step, increasing the scale from one project to the next.

The German school was not accessible to architects due to its use of mathematics which determined the geometrical form of a structure. Many of Nervi's buildings were designed in collaboration with architects, "but the constant development in style is entirely Nervi's" (Billington 1983).

3.2. Summary I.

A great deal of research has dealt with the nature of the design process in general. Designers of unconventional structures have attempted to differentiate the design process of their structures from that of conventional structures according to the way in which activities take place. Others believe that it is a cyclic process similar to conventional structures and others believe that it is a stage-by-stage one. The nature of the design process in general changes according to the nature of the problem it has to solve.

With the Industrial Revolution, the nature of buildings changed and so did the nature of the design process and the position of architects and engineers participating in it. The designers of architectural structures, who were mostly engineers, were confident about the feasibility of their designs only when those had a strict geometrical shape. The more innovative the form the more difficulties it bred. Unpredictability as far as loading conditions, cost and time were concerned was a common phenomenon. Rules of thumb and full-scale models were the designers' weapons to test and prove that their unconventional proposals were feasible. The design process was a trial and error one and most of the time this process continued, while the building was being erected. The design process occurred simultaneously with the erection of an unconventional scheme.

3.3. The new approach to the design process.

Boys (1963) suggested that during wartime the emphasis given to roofing technology bridged the gap between architects and engineers and made the rapprochement between them necessary. The collapse of the Tacoma Bridge in 1940 and other failures that occurred during the early days of reinforced concrete, such as the 23m tied-arch near Prague in 1892 and similar incidents with exhibition buildings in Paris in 1900, as well as the collapse of a hotel in Basel in 1901 (Harley-Haddow 1981), taught designers a lesson; such incidents forced them to be more cautious and avoid underestimating the unpredictability and seriousness of several factors such as wind and earthquake loads. According to Boys (1963) “the advent of these structural regulations paved the way to codified methods of design” (p. 333). Matthew Nowicki’s design for Raleigh Arena in North Carolina in 1952 was a breakthrough and the first building to adopt the principle of using counteracting cables in two directions. In that manner –that is by interlacing cables– fluttering and buffeting caused by wind loads was for the first time handled successfully. Tension was the new and fashionable word which, together with the Raleigh Arena design stimulated Frei Otto, a German architect, to obtain his doctoral thesis entitled *Das Haengende Dach* (The Hanging Roof) published in 1954. Frei Otto’s thesis employed a diverse approach to several issues of lightweight structures. However, his contribution was not only limited to issues of theory, but extended to conducting experiments, physical modelling techniques, observation of nature and application of its laws.

Modern materials encouraged Frei Otto to experiment with light structures. He studied the relationship between form and mass (IL 21) and the potential of materials to be employed for various ‘unusual’ structural types. Contemporary designers stood in awe of Frei Otto’s personality and a group of them –members of the *Institute fuer leichte Flaechentragwerke* (IL) (or Institute for Lightweight Structures)– at the University of Stuttgart- set about to establish rules for these new structural types. The means that Frei Otto used to communicate and prove his ideas advanced the design process of unconventional structures. Despite his inventiveness, Frei Otto and his team designed

structures that were not very popular. One reason, according to Goldsmith (1984), was the structures' non-permanent nature. Another reason, according to Eekhout (1988), was the monopoly that Frei Otto had, due to his reputation over the design of unconventional structures. Eekhout has pointed out, not without a tinge of irony, that:

“Presumably Frei Otto’s know-how is very select and really high-tech, highly intelligent: closed for a lot of us, normal architects” (p. 18).

Even though Frei Otto has been involved in the most outstanding unconventional structures, Drew (1976) criticizes Frei Otto’s work as failing to transform its pure rationale into total architecture. The unavoidable question is why we, “normal architects”, have failed to acquire Frei Otto’s knowledge on unconventional problems to the same degree of depth, and why contemporary designers still feel the need for his consultancy. Indeed, it appears that for a long time his role has been that of the consultant architect who is called in to solve a particular problem. Frei Otto has himself described his role in these words: “Though I have the chance to do some of the work or to help, in the last years my position has always been rather like that of a fire-department –called in if there was a special problem– and I love it.” (cited in Happold and Liddell 1976, p. 250).

Still, several building types had to be explored and erected, before the design process could somehow become less problematic. Even with the presence of Frei Otto, consistency in time and cost initially predicted could not be guaranteed. With or without the presence of Frei Otto, the design process of unconventional structures had, in general, to overcome problems. New features that appeared differentiated the design process of unconventional from that of conventional structures. It may have been expected that this differentiation would put architect and engineer on a par with one another. Instead, it bred a dissent between them that had an impact on the efficiency of the design process.

3.4. Background - Emerging different roles.

The status and position of architects and engineers in the design team and more broadly within the building industry has been undergoing a continuous change. This has been attributed firstly to changes in society's perception of the clarity of task and abilities of architects and engineers, and secondly to the increased complexity of design itself.

Up to the Renaissance, engineering as a profession was unknown. In the Renaissance, as Parsons (1968) describes, in a list of "ever famous names there is none that to the layman suggests the engineer. [...] He does not find one that brings to his mind the thought of scientific construction" (p.13). This work was done by architects and artists who were conversant with the technical requirements of both engineering (where application of scientific principles predominates) and architecture (governed by aesthetic considerations). Vitruvius refers to the Renaissance man, who would combine the two disciplines, as the "architectus". Thus, according to Parsons, if we were to try and discover the engineers of the Renaissance we would have to attempt it on the basis of whether their work showed the predominating influence of scientific rather than of aesthetic application. The lesson to be drawn from the work of the Renaissance "architectus" is that 'nowadays –when specialization and design complication makes it impossible to combine both skills– practitioners of each discipline should ideally be working along parallel, not divergent, lines that are at frequent intervals cross-connected' (ibid, p.14).

At the turn of the century there was a turning point in the assessment of the contribution of the engineer. That was due to the appearance of engineering structures such as radio towers and cooling towers, suspension bridges and high-rise buildings which technologically advanced the standards of living (Mason 1975). Great engineers like Brunel, Paxton and Maillart gained respect equal to that of the architects (Happold 1987).

The growth in the importance of the engineer's role was due not only to the improvement in the quality of life or for economic reasons, but also to his increasing

awareness of his responsibility for proposing innovative safety measures. Leonhardt (1976, a) explains that the engineers' contribution reflected the psychological effects that structures had on individuals and society in general. The "psychic safety" was translated into "comfort, well being and contentment of humans". Nevertheless, up to the 1970's, conventional buildings limited the role of engineers to determining the size and position of columns, beams and slabs (Ahm 1970; Rice 1986). Also in the 1970's, the era of advances in computer sciences, engineers shifted into the new area and their task became mainly to prepare or select the computer programs that would analyse data for the given structures.

This new situation alarmed leading engineers, when they viewed their profession as becoming too specialised. This would raise more difficulties in interacting with their fellow designers and place restrictions on their design skills and imagination. Debates went on to increase people's awareness of the situation and of the ultimate danger faced; engineers, able to understand structures and having the knowledge necessary to propose and innovate, would end up having no say in the design process (Ahm 1970).

A joint CEI/RIBA Education Group discussion took place in 1966 with the title: "Bridging the gap between the disciplines of architecture and engineering" (Concrete, April, 1968). Outstanding engineers such as Ove Arup "for service to Architecture" and Fritz Leonhardt and Edmund Happold for their original contributions in all areas of structural design, received Gold Medals. They all dedicated most of their speeches to education, referring to the causes of the "well-known and oft-deplored" schism between architects and engineers, and proposed ways of handling the problem (Arup 1966).

A great number of engineers and architects have reinforced what is an ongoing debate (Goldstein 1963; Martin et al. 1979; Wilde 1983). During the CEI/RIBA discussions there was an attempt to identify the roots of the communication problem. Members of the group concluded that, "architects are trained to develop judgemental and problem

solving ability involving interaction of factors” while “engineers put emphasis on quantitative solutions of problems in isolation” and that this was one of the roots of the problem (p.152). Moreover, it is believed that architectural students develop too little understanding over a wide field. This creates obstacles to communication with other professions which is based on a similar understanding of principles (ibid). Arup (1966) pointed out that if Architecture is about Art, then, supposing that the engineer is the antithesis of an artist, there is no common ground on the basis of which to organise a building activity. However, he continues by expressing a more compromising view when trying to link together the three opposing issues of art, “building technology or sensible building” and “commodity or the program or function”. “The sensible building would reduce the cost, commodity costs money, and art may or may not cost anything generally, and can even be more expensive, if badly handled” (ibid, p.350).

The outcome of the exchange of opinions was not against specialization, quite the opposite; it revealed the good intention of identifying the common ground for constructive discussions. As Leonhard (1976) has emphasised, architects and engineers have to realise, that they share common interests when it comes to materials, basic mechanics or aesthetics of structures, elements which are more important than mathematics.

With regard to specialisation, Mason (1975) has argued that “we need an elite, but not an expanding elite, in the professions. I do not think that mediocrity which is the inevitable result of doctrinaire egalitarianism is likely to provide the competitive thinking” (p. 510). The CEI/RIBA discussion also concluded that, in the future, specialization must increase in parallel to the increased complexity of building need.

The suggestions for improvement of the education derived from a criticism of the current formal education of engineers (there are five different approaches only in the U.K). Ahm (1970), Leonhardt (1976, b) and Wilde (1983) have suggested that to stimulate design it would be necessary to reappraise the whole process of engineering

education and training. That would include coverage of the field of mathematics, technology and science while cultivating “imagination, creative ability, artistic sensitivity and vision” (Ahm 1970, p.24). Wilde (1983) has added that the engineer has to be familiar with the design process and that can be achieved by introducing design work to engineering courses. Designing can then improve with the quality and quantity of structures, “which one has consciously seen and studied and registered mentally” (Leonhardt 1976, b, p.88).

Suggestions of ways of bridging the gap between architects and engineers focused on the issue of altering the reward system. The situation varies, of course, across different countries and cultures (Goldstein 1963). In general, though, the ethical problem for engineers, and to a certain extent for architects too, is that they are supposed to develop the most economical solution in terms of construction and maintenance cost, when the rationale behind engineering or architectural fees is that reward should be analogous to cost. Leonhardt (1976, b) has proposed that instead of producing one and only one economical design, the engineer should be rewarded, for producing “alternative designs within fixed requirements which should allow chances for better design, for innovations, for new chapter construction, thereby compiling competition in design and construction” (p.453).

3.5. Difficulties during the design process.

The factors that need to be taken into account during the design process are time and cost limitations, constraints imposed by the brief, architectural, structural, environmental and urban considerations and constraints, criteria concerning the choice of material and the design of details (Lawson 1980). To define the nature of difficulties in the design process of unconventional structures, it would be useful to look at some examples where various difficulties were encountered.

3.5.1. Time.

Rogers (1986) has explained the relationship between innovation and the time factor. More specifically, when innovation is introduced, time can be diffused and that may depend on:

- “i) the innovation decision process by which an individual passes from first knowledge of an innovation through its adoption or rejection,
- ii) the innovativeness of an individual or other unit of adoption –that is, the relative earliness/lateness with which an innovation is adopted– compared with other members of a system, and
- iii) an innovation’s rate of adoption in a system, usually measured as the number of members of the system that adopt the innovation in a given time period” (p. 189).

Happold and Liddell (1975) ascribe delays in the design of the Mannheim Garden Centre to the size of the structure “a shell of four times greater span than any other previous examples had to be completed in eighteen months for an exhibition” (p. 99). In the case of the Munich Olympic Roofs, lack of experience was to blame for the undertaking of a design program which started out on a number of paths simultaneously. According to Happold and Dickson (1974), six months were lost in this way.

Frei Otto explains why delays can be attributed to the complexity of the Mannheim Garden Centre: “the work on such buildings does not take place consecutively, much is done simultaneously. Innumerable negotiations take place. Every day, there are three to four meetings at different places with different persons” (Otto 1976, p 13).

Similar negotiations and discussions about the feasibility of the scheme caused delays to the Munich Olympic Roofs project. The scheme might not have been executed if the designers had not fought for their idea until the whole team was convinced. “Much

valuable time was spent on discussions as to whether this 'tent' roof could be built and it was only slowly that a decision was reached" (Leonhardt and Schlaich 1972, p. 113).

Herzberg (1984) attributes the delay of the erection of the Schlumberger Research Centre at Cambridge, to the:

"underestimation of the complexity of the steelwork, the dock strike, and problems with the perimeter glazing of the offices. The complexity of the steelwork seems to have been underestimated in three ways: in the design of detail, in the high degree of accuracy required in fabrication and in the extremely tight tolerance permitted in erection." (p. 58).

Happold and Liddell (1975) also claim that in the case of the Mannheim Garden Centre "the difficulties involved in the geometrical calculations were also underestimated and this had a further delaying effect." (p. 130). Similarly for the Riyadh Diplomatic Club, the control of the building geometry was taxing and time-consuming:

"Hanyang Corporation were unable to complete the work within the 19-month period set by the client. They did, however, achieve within 30 months, which was considered to be a very creditable achievement, bearing in mind the complexity of the construction.[...] There were many deviations from the original schedule, and certainly a number of design activities required considerably longer periods before they were complete..." (Happold et al. 1987, p. 38).

Another time consuming process is the use of physical models to test the feasibility of an unconventional scheme. Testing and modelling for the Munich Olympic Roofs overshadowed the whole design period (Leonhardt and Schlaich 1972). Physical model tests should have occurred more than once. Eekhout (1972, p. 32) has explained that the models for this particular project required extra, intensive pretensioning, very

intensive labour and careful work. This part of the model work absorbed a great deal of the available time.

There has been a lot of progress in the use of computers for the design process of unconventional structures. Not long ago the use of computers was very time-consuming. Eekhout (1972) argues that, if designed ten years later, the Munich Olympic Roofs computer program would have been nine times as fast.

In a number of cases, the design of the construction method was more time-consuming than the erection itself. O'Neill (1979, p. 46) comments on the erection of the Jeddah Sports Centre, saying that, although the operation took seven days, preparation was much longer. Happold reports that, "more man hours were spent on the design of the erection than on the actual erection itself" (Happold cited in O'Neill 1979, p. 46). The erection had also practical delays. Final prestressing had to be done early in the morning when the temperature was about 37°C (ibid).

Another issue that can cause delay is the difficulties the design team have in establishing special regulations or design rules. The unconventional nature of a structure does not allow for extensive use of standard input (i.e. British Standards, DIN, etc.). Time is consumed while defining the snow and wind loading.

A premature start on site was a cause of time wasted for both the Sydney Opera House and the Munich Olympic Roofs. Arup and Zunz (1969) explain that "a detailed reappraisal [...] took place and the possibility of throwing away years of work became a stark reality" (p. 112). Similarly, in the case of the Munich Olympic Roofs, the work was further complicated by the fact that, because of lack of time, many foundations had to have been built before the calculations on the superstructure were finished (Leonhardt and Schlaich 1972; Eekhout 1972).

Ealey et al. (1986) faced difficulties with the Riyadh Diplomatic Club, having to wait for components to be transported to the site.

Angelopoulos argues that delays in completing the Munich Olympic Roofs were caused by bad timing (cited in Eekhout 1972).

3.5.2. Cost.

Dr Ieuan Maddock, Chief Scientist at the Department of Industry, explained to the engineers gathered in London in October 1973 why very few projects of advanced technology stayed within their cost forecasts:

“one was that the man with the idea failed to appreciate that for each unit spent on research and development, the project would require ten units to bring it to the market place –and might need as many as a hundred units to fully exploit the market [.....]. Another reason for escalating costs was that the difficulties bound to arise as projects expanded from the conceptual to the practical scale are consistently underestimated. The error is particularly great when disciplines outside the person’s own knowledge and experience are required, as is increasingly the case with high technology projects today. These other disciplines the engineer tends to dismiss as ‘mere engineering detail’. A third reason for escalating costs was deliberately underestimating by the engineer, who even argued sometimes that if their estimate were to include realistic margins for contingency the project would never be approved at all” (cited in Fishlock 1986, pp. 149-150).

In line with the above, Billington (1983) attributes the unpredictability of cost of innovative structures to their scale. However, he argues that this happens initially, and that once the idea is put into practice prices will drop. Having said that, it is debatable whether it is appropriate to define a structure as innovative when it is widespread and multiply applied.

Often innovation has come to the history of architecture and engineering as a breakthrough in materials science. Structures tend to show their lightness and that can be achieved by “stretching” the limits of the materials which comprise it. The medieval designers, for instance, had similarly “stretched” stone into the skeletal Gothic cathedrals (Billington 1983). Cost should not be an obstacle to creativity in structural engineering (ibid). After all, efficiency in the use of minimal material was the hallmark of the work of Felix Candela and Frei Otto. However, there are times when lack of familiarity with the material and its use can lead to unpredictability in cost. That was the case at the Mannheim Garden Centre. Happold and Liddell (1975) have reported:

“The rough calculations had already indicated that the shells were too thin and this was stated. However, the amount and extent of thickening required was uncertain. It was agreed that some provision should be made for extra material and so prices were obtained for areas of doubled laths”
(p. 106).

Eekhout (1972) expressed similar ideas about the use of materials for the Munich Olympic Roofs. “Till now it appeared that it is always cheaper to add material afterwards than to take measures of which really no one knows the effect”. It is obvious that the cost increases with the amount of material added in order to achieve safety. In the case of the Mannheim Garden Centre, if the span of the laths had been doubled, 100×100mm laths would have had to be used and the grid would have become four times heavier (Happold and Liddell 1976).

As stated earlier, Billington (1983) believes that the cost inevitably rises beyond predictions when the unconventional project demands a great number of specialists to solve particular problems. Using the Sydney Opera House to support this argument, Giedion (1964) pointed out that when specialists have to be called in to solve particular problems such as structural engineers, acoustic experts, heating experts, stage

construction experts, the budget has to be increased to pay for the man-hours spent by the specialists.

The right moves during the design process can prevent a slip in cost prediction. These moves concern the design of detailing, considerations on structural and environmental savings, savings in computer time, and design of the construction method to be used. Happold and Dickson (1974) argue that “long span structures inevitably cost more and are nearly always conscribed by their details” (p. 333). For instance, at the Munich Olympic Roofs, these details were the node points. Liddell (1987) agrees that “fabrication costs are obviously increased by the amount of detailing, cutting and sealing of fabric, and so on” (p. 378). He has concluded that larger areas of fabric usually result in lower unit costs. More specifically, he argues that, at the Riyadh Diplomatic Club, the cost of radial cables and the boundary cables were probably less significant. In conclusion, it is suggested that, “larger areas work out more cheaply per m² than do the smaller ones” (cited in Happold et al. 1987, p. 378).

There are also many considerations that have to be taken into account as far as building economics and energy savings are concerned. In some cases energy exchanges can be minimised by exposing the structure. At the Schlumberger Research Centre at Cambridge, Herzberg (1984) explains the advantage of an exposed external structure. He adds that this reduces building volume so that less heating is required. This saves on cladding and capital costs are less. There is also a better protection of the framework from an internal fire. The disadvantages are the extra cost of corrosion protection, the increased thermal movement of the structure and the expense associated with detailing of structural elements”. For this particular building Herzberg remarks that it is “simplicity and minimisation of detail and components that matters” (p. 51). Other studies, such as that of Geiger have supported the view that the “skin” of the building in conjunction with the structure can contribute to energy savings. Geiger (1986) remarks that, “the use of a single membrane in extremes of heat and cold can lead to the structural savings being exceeded by the increases in ventilation costs” (p. 383).

Eekhout (1972, p. 48) relates the complexity of detailing to the expenses required to cover the computer time necessary. Discussing the case of the Munich Olympic Roofs, he argues that on a cable net “computer time depends mainly on the number of intersection points, which grows about squarely with the number of cables” (p.48). He suggests that exceptionally profitable savings on the expensive computer time are possible when only a part of the cables of the final cable net is calculated, and the cables in between are interpolated afterwards. He also remarks that “local structural conditions which limit the selection of supports or system points have a far reaching influence on the economy of the overall structure” (p. 56).

It appears that the design process of unconventional structures should involve the design of the construction method. This could at least prevent the overrun cost as far as the construction method is concerned. Additionally, a complete and well-thought out construction method enables the communication between the design team and the contractor who will eventually execute the structure. The same is true for conventional structures. However, for conventional structures there are various well tried and established ways of erection.

Inadequate design of the construction method combined with time pressures leads to premature fabrication and work on site when the design has not yet been adequately crystallized. Baume (1967) has underlined that this was the reason why so much extra was added to the cost of the Sydney Opera House:

“in justifying the huge jump in cost of stage I from \$2.8 million to \$5.3 million (some of which was met by agreement and the rest resulted from a successful claim) the contractors, Civil and Civic, said that in three years 700 drawings had been issued (almost half of which had come after the expiry of the original contract time of twenty-one months), and that there had been 695 amendments issued [...] last minute design changes” (p. 10).

Other factors that can dramatically add to the cost are the accessibility and adaptation of a building to the context. According to Langner (cited in Happold and Liddel 1976), the overall cost of the Mannheim Garden Centre was influenced by the bad soil and the support for the ten meter high hill that had to be created as well as the accommodation of access to the extraordinary ground plan shapes and the landscaping.

“The costs of the roof (DM 3,586,000) to the roof surface (9,790m²) result in a price per m² of DM 370. The total costs (DM 8,932,000) per usable area (10,500.00 m²) result in a price of DM 850 per square meter” (p.179).

Cost and economy are two issues that have different values in the short or long term. According to Medlin (1984) “there should be the efficient utilization of resources over an appropriately planned project life span that interrelates the material and energy expenditure of initial construction with life cycle operating and maintenance cost” (p. 124). The justification for the choice of an unconventional structure must be strong enough to counterbalance the short life-span that the structure might have. The material industry is making progress in resistance to ageing. The initial cost of a durable material, which does not need to be changed frequently, well designed details, that prevent failures and protect it from corrosion, heat loss etc. as well as the efficient design of services which implies energy savings in the long term, are all criteria which must be taken into account.

3.5.3. Site considerations.

According to Scheuermann (1991), as far as the urban context in which curvilinear structures can appear, there may be two types of situation:

“it depends whether the important buildings are tessellating with the surrounding ordinary pattern, or whether they are freestanding objects, only surrounded by the ordinary in a certain distance.” (p. 34).

In the former case, the building has to adapt to the surroundings and the adaptation is seen mostly architecturally and aesthetically. In the latter case, this adaptation is seen as adjustment to the landscape and exposure of the building to the climatic conditions of the site. In nature, straight lines do not exist. Although controlled curvilinear forms hardly exist in nature, it can be argued that it should be an easier task to adapt a curvilinear building to the landscape rather than to an urban context. This gives a reason for the erection of curvilinear structures mostly in an open space.

The proposed scheme for the Munich Olympic Roofs not only encountered “a number of technical difficulties (water drainage, snow and ice sliding, wind load, etc.)” but also had to deal with the size of the building which was enormous (80 000 spectators). To tackle the gigantic dimensions of the artifice the designers decided to sink these buildings into the landscape “reducing the visual size” (Eekhout 1972; p. 19).

Langner (cited in Happold and Liddel 1976) describes the structural type chosen for the Mannheim Garden Centre as a dialogue between landscape and structure: “a freshly contoured undulating landscape as the preliminary link to the grid ‘hills’, with those terraces it is closely connected” (p. 249).

Similarly, Gribl’s (Spring, 1980) aspiration for the Munich Aviary was a light structure that does not offend the landscape of Munich and looks like a cloud. At the Diplomatic Club in Riyadh, a combination of local architecture and tradition had an influence on the design team which decided on a masonry wall that would have tents attached to it and would not disturb the landscape. Ealey et al. (1986) recall: “working models were used to develop the shape and sitting of the wall, to obtain a built form responding sympathetically to the desert landscape extending to the edge of the plateau” (p. 425).

Allsopp (1988) explains that although the choice of a rigorous geometrical form for the Calgary Ice Stadium may not go down in architectural history as a particularly interesting building, “a case could be made that it is a fair reflection of the state of

Canadian architecture, and it does illustrate two directions for a regional or national architecture (if such things actually exist)” (p. 18).

3.5.4. Environmental considerations.

The environmental success of a building depends upon the use of the building and the internal micro-climate this use generates. The structural advantage of curvilinear structures in covering long spans explains why these structures were originally used for sports halls, air terminals and hangars or factories, where the demands for acoustics, sound and thermal insulation were low. The advances of the material industry, promising a longer life span for unconventional structures, extends their application to more permanent buildings and to buildings of various uses.

The decision-making must take into account function and microclimate so as to design any unconventional structure properly. According to Giedion (1964) the function of the Sydney Opera House suggested shapes which could achieve efficient acoustic performance. These shapes were chosen initially by the architect among many other alternatives. Regarding the micro-climate as another element influencing the decision making, the examples of the Jeddah Sports Centre and the Calgary Ice Stadium illustrate how adaptations relating to environmental factors are made. In the first case, because of the hot climate, provisions had to be made for natural and artificial ventilation, whereas in the second case, despite the cold climate which favours the ice rink, the building’s specific function, which requires the accommodation of spectators, made provision for additional heating unnecessary.

It is interesting to distinguish between two different attitudes that designers appear to have towards climatic constraints. One is to preclude a structural type which could bring difficulties and select one that is less problematic. The other is to challenge the design and explore the use of a structure which is expected to cause complications. The former was the case with Calgary Ice Stadium. According to Brancatelli (1984), the choice of lightweight concrete meant that large volume members could be hoisted into

place by limited capacity cranes. This contributed substantially to solving the problem of temperature swings, one of the characteristics of Calgary's climate. The latter was the case with the Mannheim Garden Centre, where an unusual structure was selected and that caused complications.

As Happold and Liddell (1976) explain, during the design process of the Mannheim Garden Centre there were no German DIN standards from which designers could get data. Additional testing had to take place in order that the values of wind and snow could be determined. Moreover, the use of the enclosure space for the Garden Centre posed demands on ventilation, heating and cooling. Again the lack of standard input was another obstacle for the design team (Goldbaum et al. 1976).

The design team of the Riyadh Diplomatic Club spent a great amount of time deciding on the climatic behaviour of the building, which was subject to severe changes in the middle-eastern weather. Ealey et al. (1986) recall:

“to help reduce solar heat gain and to reduce the drop in temperature on cold nights, it was decided to include a lining membrane of lightweight teflon coated glass cloth...One of the worries with a translucent lining is that it will become dirty with dust, and possibly condensation, falling on it. The membrane was subsequently redetailed with site joints on the seam lines.” (p. 433).

In the cases of both the Sydney Opera House and the Munich Olympic Roofs, the peculiarity of the structures' form and the lack of available climatic data were a problem. Concerning the former, Arup and Zunz (1969) explain that wind tunnel tests were necessary in order to define the wind loads on the curved surfaces. For the Munich Aviary, snow was the climatic factor that could overload the structure. This was constructed to have a weight of only 2kg/m^2 , but provision made for a maximum of one metre high snow brought the total load -dead and applied- up to nearly 100kg/m^2 (Spring 1980).

3.5.5. Materials.

Gordon (1988) has discussed the relationship between materials and design. The challenge is enormous when the exploration of the design avoids using the material in a conventional and traditional way. Rice (1992) has further explained that:

“the real issue in design must be to break the mould of industry controlled predictability which dominates so much. The reaction of the public has become conditioned. One way of doing this is to take materials and change the context of their use. Another is to introduce new materials into a normal and predetermined context” (Rice 1992, p.4).

The design of unconventional structures employs both methods. Disputes among members of the design team may occur at the time when the nature of the material to be used needs to be decided. It is possible that behind such disputes lie the different objectives of the disciplines involved and that these objectives depend on the background knowledge that each discipline has related to materials and their properties. Some evidence supporting the above suggestion is given by Arup and Zunz (1969), two of the principal engineers of the Sydney Opera House. They stressed that “the architect’s original conception was that only basic materials, such as concrete, steel, wood, glass and, course, ceramic tiles, would be exposed.” (p.119). What was missing was the knowledge of how to fit these materials with the decided form. The use of shells made of concrete which the architects envisaged was regarded as non-feasible and uneconomical by the engineers, who in order to satisfy the architects’ preference for this material suggested concrete ribs. The dispute in Munich Olympic Roofs started when timber was suggested as an appropriate material to cover the roofs (Eekhout 1972). However, due to its vulnerability to oscillation, the idea of using timber was rejected. The final decision to use perspex was determined by the material’s transparency, its dark tinting (grey-brown), its durability against mechanical influences and decomposition, and its fire resistance. (Eekhout 1972 p. 68). According to Happold and Liddell (1976 p. 248) the main reason why timber was underused as a

structural material was, that its properties were less exact than those of man-made materials.

Similar difficulties in deciding upon materials are described by Spring (1980) who argues that although the form of the Munich Aviary had been defined, the team could not determine what material would be suitable: “it was Buro Happold’s brainwave that if the mesh were distorted into a shape that formed a series of double curved surfaces it would gain sufficient strength to be used as a wide span structural material.” (p. 30). The example of the Munich Aviary is also interesting for demonstrating the effectiveness of using a non-building material in a novel manner. More recently, the case of Hooke Park has, according to Dormer (1990), demonstrated that previously neglected materials, such as round-wood timber, can prove useful as well as profitable.

3.5.6. Construction detailing.

The design of details is of major importance for the feasibility of unconventional projects. The differences between conventional and unconventional structures becomes apparent when the detailing takes place. Most of the designers find the designing of details very challenging.

Arup (1969) remarks that the design team of the Sydney Opera House –an “unusual” structure–, introduced several “new” construction details such as the connections between ribs, in order to resist lateral tensile stresses due to temperature changes (p. 129, b).

In the design process of unconventional structures, the design of details is high on the list of priorities. That is because detailing can determine the overall geometry of the structure. That was the case with the Sydney Opera House. Croft and Hooper (1974) recall:

“the details were developed in parallel with the computer programs and the geometry. This was essential because the overall geometry determined

both the size of the members and the form of the connections while these in turn influenced the overall geometry” (p. 219).

Detailing concerns both architects and engineers. Elegance of detailing is a quality equally pursued by both disciplines. However, the general concern of detailing may appear to be based on different objectives. In reality, these objectives are interrelated. The points that are designed in detail in an unconventional structure are the ones that redirect the forces, and that seems to be the engineer’s responsibility. The redirection though, depends also on the geometry of the structure and that seems to be the architect’s responsibility. An example of interrelated objectives is the aerodynamic shape of the gutters of the Munich Olympic Roofs, designed to avoid wind turbulences (Detail 1972). Happold and Liddell (1975) confirm the relationship between structural-architectural considerations and details on the design of the Mannheim Garden Centre:

“the work of detailing the grid shell can be broken down into a series of design decisions. The details of the grid, typical node point, ties, blocking pieces are related to the non-linear analysis and involve stiffness. The details at the boundaries were calculated on a strength basis with normal factors of safety, but were influenced by geometrical requirements.” (p. 123).

They also stress the impossibility of using standardized components on an unconventional structure which would reduce the time spent on designing details from scratch or constructing newly designed non-standardized components. One of the implications of using newly designed components is the lack of standards to secure the safety of the design. At the Mannheim Garden Centre, in order for the construction to be realised economically and technically, joints and fastenings, which were not included in the German timberwork standards had to be used. Numerous experiments had to be carried out before sufficient evidence of their performance had been collected (Happold and Liddell 1976).

The relationship between supporting and supported structure is determined by the design of details which in turn determines the feasibility of the desired form. The mast heads often are the key details that make structures work (see Pugh 1989; O'Neill 1979; and Parkinson 1980). The design of mast heads was the key detail in the case of the Jeddah Sports Centre and the Munich Aviary.

Discussing the case of the Diplomatic Club in Riyadh, Ealey et al. (1986) have stressed the importance of designing the points that connect the tents to the rigid wall: "two alternative concepts of attachment of the "roses" to the wall were initially considered. The first was to separate the structure of wall and tent, and use a masted tent with boundary connection to the wall. The second was to use the wall itself as a primary high level support" (p. 426).

Elegance and detailing must be closely linked in order for the overall design to be successful. Eekhout (1972, p. 62) points out that for the Munich Olympic Roofs, the demand for transparency expressed at the brief was destroyed by bad design of the joints, so that black rubber finally dominated the visual appearance of the roof.

Bobrowski (1987), one of the engineers of the Calgary Ice Stadium, attributes the simplicity of detailing to the simplicity of the building's shape. This simplicity assisted in the controlling the construction time.

3.5.7. Problems with authorities.

Like conventional projects, unconventional ones have to be approved by the local authorities. Even though this may sound an insignificant matter, it is one which is time consuming and adds to the tension among the members of the design team. The Sydney Opera House, the Munich Olympic Roofs, the Mannheim Garden Centre and the Munich Aviary were projects that all had to overcome such difficulties and persuade the Local Building Authorities of their feasibility and also 'acceptability'. Some project proposals were initially rejected and the design team had to redesign parts of these

proposals. At the Munich Aviary, the Bavarian building authorities refused to adjust their codes to encompass the more elegant prestressed foundations proposed.

3.6. Summary II.

In this chapter it was suggested that the design process is evolving, dependent upon social needs and changes in the society, as well as advances in materials, technology and computer science. This continuous evolution demands changes and reassessment of the roles of designers regardless of the discipline they belong to.

The design process is a problem solving task which appears to be becoming more complex. Evidence indicates that the process becomes more complicated when innovation is introduced. That is because, apart from the usual difficulties, problems in estimating time and cost, in convincing the client, authorities and public, problems in choosing a material the adequacy of which is unknown, and difficulties in designing new details which are not dictated from existing building standards, may appear. Additionally, differences between conventional and unconventional structures may arise due to the different “language” spoken by the disciplines involved in the design process. Moreover, lack of a systematic approach to identify the rules that govern the design process of unconventional structures may create additional difficulties.

PART II. THE NINE BUILDING CASE STUDIES.

Chapter 4. Methodological Framework.

4.1. Introduction.

This chapter comprises two parts. The first part presents the theoretical considerations behind the decision to adopt specific methods for collecting and analysing data. The second part presents the actual steps taken and the processes adopted.

As stated earlier, there are two research questions in this study:

Research question 1: Are there differences between the design process of unconventional structures and the design process of conventional structures? If so, to what are these differences attributed?

Research question 2: What are the difficulties that make the design process of unconventional structures more problematic than the design process of conventional structures? To what are these difficulties attributed?

During the first phase of the research two pilot case studies were carried out. An architect was interviewed for one study and an engineer for the other. They were asked to recall the design process of a particular unconventional project, as they had experienced it. During the second phase, seven main case studies were conducted. One architects and one engineer who had participated in the design of each of the projects were interviewed.

4.1.1. Methodology adopted in the present study.

According to Oxman and Oxman (1992) design process models fall into two categories: the theoretical global models e.g. analysis–synthesis–evaluation, and “the particularised descriptions based on empirical research into the behaviour of human designers” (p. 118). Protocol analysis, as Ericson and Simon (1984) have explained, is the empirical

technique which employs documentation and analysis of designing “as a basis for the study of cognitive process”. Dubois (1987) has talked about ways of analysing and understanding the design process by employing “archival material for interpretation in place of direct observations and recorded protocol”. According to Oxman and Oxman (1992), “these research methods are related to the concept of state descriptions as a sequence of representations which can be used to analyse designers, their moves and strategies. Through this research the dialectics of design can be formalised and modelled. [.....] The objective of such research is to theoretically simulate design transformations in order to identify operations and strategies which might be employed in cognitive processes of design” (p.118).

A similar approach was adopted in the present study, where participants recalled operations and strategies during the design process of a particular building. The idea of using “respondents’ own accounts on specific data”, according to Harré and Secord (1972), strengthens the validity of the research.

Justifying the methods of data collection and analysis.

Qualitative research was considered more suitable than quantitative research because it is more sensitive to the exploration of reasons and causes (Stoecker 1991). Moreover, Mostyn (1985) supports the idea that when dealing with issues of communication, such as those which characterise the design process, quantitative analysis is not sensitive enough.

According to the subjectivistic approach, people are seen as the creator of their social world within which they interact in a conscious manner. Thus, the task of the researcher is to understand this interaction from the subjective viewpoint.

The subjective approach is synonymous with qualitative research in groups. In the 1970’s support for this approach emerged as a result of the dissatisfaction with the positivistic tradition. Morgan and Smirich (1980), for example, propose that: “once one

relaxes the ontological assumption that the world is a concrete structure, and admits that human beings far from merely responding to the social world may actively contribute to its creation, the dominant methods become increasingly unsatisfactory and indeed inappropriate” (p. 498).

As Bryman (1989) suggests, there are several factors which distinguish qualitative from quantitative research when looking into organisations. Firstly, with qualitative research there is maximum attention paid to the context and secondly, there is much significance given to data interpretation. The qualitative approach is therefore much more effective in dealing with the aspects of the process of an organisation. This results in discovering more about the dynamics of the organisation. In uncovering these aspects of the process the qualitative researcher employs a non-structured approach.

Social scientists have talked about the appropriateness of qualitative research in an organisations of the size of a design team, and of problem solving tasks, like the design process. More specifically, as Canter and Kenny (1982) have explained: “the special problems of evaluating the physical environment stem from two related factors: (i) the epistemological problems associated with distinguishing between the psychological and the physical, and (ii) the professional problems associated with contributing to decisions made by people whose training is essentially concerned with the manipulation of physical artifacts, such as engineers and architects” (p.146).

Studying the social processes in small groups, Moreland and Hogg (1993) have included the disciplines of architecture and engineering in their case studies: “[The study included] a variety of disciplines, including psychology, sociology, business, speech and communication, and even engineering” (p.1).

The definition of the case study by Schramm (1971) illustrates clearly the appropriateness of the approach in line with the current research questions: “the essence of the case study, the central tendency among all types of case study, is that it tries to

illuminate a decision or set of decisions: why they were taken, how they were implemented and what was the result” (p. 22).

Yin (1984) has also described the case study as follows “case study is an empirical enquiry that investigates a contemporary phenomenon within its real life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used” (p. 23).

The case study as an approach to organisational research fulfils many objectives. McClintock, Brannon and Maynard-Moody (1979) suggest some objectives of using the case study approach: “the goals of the qualitative case study are: (i) to capture the frame of reference and definition of a situation of a given informant or participant and thus to avoid instrumentation artifacts of standardised measurement procedures (ii) to permit detailed examination of organisation processes (iii) to elucidate those factors peculiar to the case that may allow a greater understanding” (p. 612).

The decision to use a qualitative multiple case study design in the current research emerged as a result of the research questions and the aim of finding the process behind design. Becker (1968) suggested that the exploratory case study provided an ideal method for the study of process. In exploring these questions, the case study approach offers many advantages over alternative approaches, many of which are incorporated in the definitions above. One of the most important of these advantages is that the case study gives the possibility of the charting of elements or process models within the organisation. Burgelman (1983) and Lincoln and Guba (1985) see the case study as an ideal way of providing a detailed description, thereby obtaining a clear contextual insight into the complexities of the process.

In the current investigation, the case studies provide a view of the design process and the influence of its constituent elements as a function of the design team’s approach. Yin (1981) outlines four advantages which show further the appropriateness of the case study for the present investigation.

Firstly, the case study is appropriate for the how and why questions. In the current research we are interested not only in how design teams incorporate the diverse elements of the design process but also in why certain factors are taken into account.

Secondly, a case study allows a holistic real life investigation to take place. This is crucial to this research as it seeks to explore the design process framework within the context of other demands on the design team, thus allowing the meaningful characteristics of real life events to emerge. This could not be completed by a method that distanced the researcher from the design team resulting in an approach that measured from the outside instead of explored from the inside.

Thirdly, the case study can also ask the how and why questions of contemporary situations without the need for control. Thus, the researcher is not forced to box off the design team from its environment and to use a strict and perhaps artificial measurement. The present approach leans more towards allowing design teams to identify the crucial elements from their own perspective instead of choosing from a pre-defined range of options constructed by the researcher. The researcher in this case is able to interact freely with members of the design team without the constriction of a time frame or controlled interaction.

Fourthly, the case study enables the researcher to deal with a variety of information sources. In terms of the present research goals this is important, as it enables the researcher to gather more information than from a single method. This is seen as important for gaining a detailed picture of the whole design team and also as a means of cross checking or anchoring different discoveries that emerge during the research.

The methods used in the current study to collect the necessary data were the semi-structured depth interview (primary source of data) and the collection of documentation (secondary source of data).

Viability of the case study.

However suitable the case study may be as a research method, researchers must be aware of possible dangers so as to overcome common criticisms. Researchers must ensure the presence of four components in their research. These are according to Yin (1988), Miles and Huberman (1985): internal validity, external validity, reliability of the research and construct validity.

Internal validity: research is in general terms valid internally, when the inferences drawn are correct. Since in qualitative approaches interpretations can never be seen as correct or incorrect, data verification means, for example, an attempt to evaluate whether there are similarities across accounts.

External validity: research is in turn valid externally, when its findings can be generalised, at least to an extent.

Reliability: research is reliable, when it manages to minimise errors and biases. This problem, according to Mostyn (1985) is dealt with by using coding and justifying research interpretations by basing them on evidence (e.g. providing the actual accounts of interviewees). Yin also claims that a study can avoid errors and biases when it has rich documentation.

Construct validity: research is valid when it uses multiple sources of evidence.

The present study aimed to include all four of these components. The study used multiple sources of evidence, that is, architects' and engineers' reports, as well as documentation, to encourage convergent information. That, coupled with the fact that respondents were key informants, increases construct validity (Yin 1988). Finally, the present study collected information from both current documentary and respondents' own accounts, in an effort to ensure reliability.

The investigation of various aspects of the design process led to inferences about the causal links between participants' beliefs and the decisions they made during the design

process. (It is not possible, for this type of exploratory research, to objectively evaluate the internal validity of the inferences). In an effort to ensure its external validity the study employed as case studies projects of different structural types which could however be categorized under the overall title of unconventional structures. This allowed for certain generalisations within the specific category of unconventional structures.

Sources of evidence.

Yin (1988) proposes the use of the following sources of evidence: i) direct observation. Direct observation, as Brenner, Brown, and Canter (1985) have agreed, produces a closer relationship between the researcher and the object. ii) Use of documentation, which together with other sources increases the reliability of the research. iii) Systematic interviewing, which is discussed in more detail below.

Systematic interviewing – questionnaire design.

The means of acquiring evidence from interviewing can either take the form of a questionnaire, that has to be followed strictly and poses closed questions (structured interview), or of an “interview guide” (Brenner 1985), using open-ended questions that are not followed in a strict order (semi-structured interview). Wilson (1985) has proposed three principles for questionnaire design, and these were taken into account when designing a questionnaire to be used in the preliminary phase of this study. He suggested:

- preliminary design work on the areas to be explored in the interview;
- question wording and sequencing;
- physical design or layout (p. 66).

In order for the questionnaire to be designed so as to meet the research objectives of the study as well as the requirements for the interview situation, Yin (1988) also argues

that the researcher has to study so as to have a firm grasp of the issues being examined. The literature that the researcher goes through formulates the questions of the questionnaire and determines the issues that have to be studied.

In the main case studies, as will be explained later on, an interview guide with open-ended questions was eventually employed.

Skills that the interviewer must develop.

The interviewer must develop certain skills so that the interviews will be effective. The interviewer must ask good questions, which means that the questions must be clear and comprehensible to the interviewee. However, the expected answers must not be obvious, in other words the questions have to be non-directive (Brenner 1985). In general the interviewer has to maintain a neutral stance. The interviewer has also got to be a good listener and patient enough not to interrupt the respondent. Interruptions are, nevertheless, allowed when the researcher needs to clarify points that were not clear at first and when the interview is “going off track”. The researcher has to be flexible and adaptive with respect to the interviewees’ ideas. If contradictory evidence appears between two or more interviewees in the same case study the investigator has to find the “truth”. Occasionally, therefore, the researcher’s ability to read between the lines can be extremely useful. It is obvious that the interview is more effective when respondents are cooperative (Wilson 1985).

Pilot studies.

It is useful to have pilot studies preceding the actual case studies. The pilot studies – chosen for their accessibility or geographic convenience– help the researcher refine and clarify the concepts that he or she intends to use in the final case studies. The pilot studies can be less focused than the ultimate data collection plan, indeed one of their roles is to focus the research plan. Finally, the reports from the pilot studies can give an idea of how the data can be classified and analysed.

4.1.2. Classification and analysis of data.

The next step is the conversion of the raw material that has been collected into scientific data (Brenner, Brown and Canter 1985, p. 3). First of all, this material has to be classified. The way that the researcher classifies the data has to do with the way that this data will be later analysed and vice versa. Dijkstra, Van der Veen and Van der Zowen (1984) have proposed that one way to classify the data is the code procedure.

Process of analysis of data.

A general tactic by which hypotheses can be formulated and tested is, as Mostyn (1985) has suggested, the “funnel”, that is, moving from general to specific issues. In the present study, the design process has been seen as “a regular, every day process where people’s interaction leads them to inferences on each other’s claims, arguments” (Mostyn 1985, p.118). The same author has also explained that the open-ended material that results from the selected type of analysis is the proof for or against certain hypotheses or their evaluation. The collected data must guide the analyst to revise ideas or discover new hypotheses. The data must also be used to support any conclusion drawn in the form of quotations; “proof-quotes” preserve the language of the respondents. Non-verbal communication and tone of voice have to be taken into account. In the present study comparison techniques and explanation building theory were used, that is, analysis of data by building an explanation about the case. This, according to Yin, can be achieved by stipulating a set of causal links about it. He has also claimed that if this approach is applied to multiple case analysis it means also the application of cross-case analysis, not simply an analysis of each individual case. In fact the present case study is a multiple case study, for it employs qualitative research questions on more than one case study (Yin 1988).

The methodology of case studies.

Research design.

A strategy had to be adopted in order for the study to achieve its aims. In the first phase the issues that had to be dealt with were;

- i) the questions that had to be asked of the informants,
- ii) the way that these questions had to be asked,
- iii) the choice of the case studies and
- iv) the choice of informants.

Each of these four issues raise further questions. More specifically:

- i) Defining the research questions. The literature is limited to descriptions of the architecture and engineering of the projects and sometimes to criticism on the cost or time consumed on the project. Further and original information was necessary on the design process of the projects that were to be studied.
- ii) Finding ways to ask questions. The pilot case studies showed that a structured questionnaire was difficult to follow.
- iii) Choosing the case studies.

In the present study, neither the chosen projects nor the interviewed participants were considered as the case studies. The case studies were the design processes of the projects selected. The necessity for further and original information concerning various projects, was the criterion for focusing the study on interviews and documents taken from members of the design teams. The choice of these projects was not made with the purpose of criticising the particular buildings. Instead the criteria were the following:

- all projects fell into the category of unconventional buildings as defined by the present study (see chapter 1);
- the design team that contributed to the design consisted of both architects and engineers;
- the participants were alive to report;
- difficulties and problems during their design process were reported in the literature.

iv) Choosing the informants.

The interviewees, one architect and one engineer for each project, were chosen from lists of contributors as these appear in publications. Interviewees were “key persons” and/or senior members of the design teams. In addition, it was essential for reasons of professionalism and the protection of participants’ reputation to use individuals’ information anonymously. This was also thought to encourage a frank, sincere and hopefully revealing dialogue. Having their identity known could make them more cautious as to what they would report.

4.1.3. The adopted methodology. Phase I.

Interview guide design.

The interview guide for the main case studies (see Appendix 2), which followed the questionnaire (see Appendix 1) employed in the pilot case studies, was structured in sections that helped the coding procedure and was used to classify and analyse the data. Having taken Wilson’s principles into account the interview guide was constructed and divided into eleven sections (Wilson 1985). The issues involved were:

- The relationship between client and design team, the client’s contribution and main concerns.
- The construction of the brief, its possible flexibility or rigidity, changes if any.

- Time and cost restrictions, overrun in time or cost, if any.
- Environmental, planning and urbanistic considerations. Climatic behaviour of the building, site restrictions and influences of these aspects on the design.
- Interrelations and interaction between the members of the design team. Contributions, disagreements, domineering figures.
- Decision making, alternatives, justification of the crystallisation.
- Choice of material, restrictions and allowances.
- Buildability, architectural and structural details; feasibility of the chosen building type.
- Means of communication in the design team.
- Evaluation of the design process–assessment of the resulting building.
- General questions on education of different disciplines and exchange of information.

Description and analysis of the interview guide.

The questions comprising the interview guide had two intentions; firstly, to add to the technical information about each case study, the history of the project and the participant's contribution and position in it, and secondly to gain an insight into the design process. Information on the formation of the brief, the issues of time and cost, environmental, planning and urbanistic considerations, choice of material, buildability and detailing were discussed with the first set of questions, the technical ones. The other set –the exploratory questions– referred to the interaction of individuals and decision making. In order to enmesh the two sets of questions, exploratory ones were part of the first set.

The second set of questions aimed to give an insight into the interaction between participants of the design process, conflicts and problems.

Preliminary work.

It was thought important to classify unconventional structures into categories, so that one representative building of each category could be used as a case study. By taking every possible category it was hoped that generalisable conclusions could be drawn. The following six general categories were chosen: i) tents, ii) cable-nets, iii) concrete shells iv) grid shells, v) inflatable structures and vi) air-supported structures. They are all long-span structures that cover column-free spaces with the least material. Inflatable and air supported structures were excluded from the present study for the following reasons: i) They employ air in compression as their main element and therefore they differ from the rest in that very important aspect. ii) In the researcher's opinion, the architectural vocabulary of inflatable and air-supported structures is rather finite and therefore innovation is limited only to technical improvements of the structural details already employed. Because there are "standard types" of inflatable and air-supported structures available on the market, the design process of these structures cannot be seen as comparable to the design process of the rest.

Attempts before the crystallisation.

Initially, there was an attempt to collect data by following the method of direct observation and attending meetings between architects and engineers on unconventional projects that were being designed. After the first two attendances it seemed that the study would not advance for several reasons. Firstly, there was no available literature on the projects that were being studied and secondly, the study could not have been completed before the projects were finished buildings. Completion of the buildings was considered necessary before their design process could be evaluated in terms of effectiveness in collaboration, duration and cost. Thirdly, the constraints of a research project that could be undertaken only among projects being currently designed and built would imply that perhaps the buildings to be studied would not fulfil the criteria discussed in paragraph 4.1.2 and it might have been difficult for the findings to be generalizable, and therefore for the research to be validated externally. Fourthly, the

researcher's presence would probably influence the dynamics of the social-working environment, so that the picture obtained may not have been as authentic as it could have been otherwise. Lastly, the researcher (herself an architect) would be at risk of identifying more with the architectural discipline, and be partial in her evaluations of what was actually taking place. Eventually, the idea was abandoned and the material collected was not considered worth presenting in the thesis.

Pilot studies.

Two case studies preceded the main case studies. Their choice was based upon geographical convenience and accessibility. The interviews were conducted with the architect of the one and the engineer of the other project. This first attempt indicated in future interviews that collection of data from both disciplines and search for contradictory evidence was necessary. In other words, it was considered necessary to attempt cross-case analysis and comparisons between reports of the participants.

After the pilot studies took place the form of the interview changed. The closed questions that were originally posed were eliminated during the main case studies, because the information they provided was too restricted. The original questionnaire did not allow the possibility of major changes of the issues chosen to be discussed. In the main study, therefore, the interview adopted an open-ended, semi-structured form. Additionally, respondents in the two pilot studies suggested better ways of phrasing the questions. The results of these pilot studies were included in the body of reported findings playing, a complementary role.

Choice of the case studies.

Based on the criteria set by the researcher for choosing appropriate studies (i.e. unconventional structures, live contributors, etc.), a large number of projects satisfying the above criteria was initially identified. An additional criterion had to be set in order to reduce the number of case studies down to four, one of each type of unconventional

structures. After completing the four case studies, it was decided that additional ones were necessary because of insufficient information provided by some respondents (see chapter 6). The procedure for selecting the additional ones was the same one, according to the criteria set out in section 4.1.2. The additional case studies were of the same category as the ones which did not provide sufficient information. The literature review revealed a number of appropriate buildings that not only fulfilled the above practical criteria but were also found to be adequate for the study of theoretical issues that this research intended to examine.

After this final addition, which increased their number to nine (including the two pilot studies), the number of case studies was considered sufficient to illustrate and test the hypotheses. A larger number would have been more time-consuming, probably without offering significant further information. On top of that the qualitative analysis, by definition, explores case studies in depth, so that a greater number would have been impossible to handle within the time limits of the present research.

The first two pilot case studies were the Sydney Opera House, a concrete ribbed shell, and the Institute of Lightweight Structures, a cable net, in Stuttgart, Germany. Data was collected through interviews with one of the engineers of the former project and one of the architects of the latter. The two interviewees' reports raised different issues concerning the design process, revealing conflicting viewpoints. It was therefore considered necessary, and of great importance for the construct validity of the research, to interview both architects and engineers in the main case studies. There was an attempt to apply this principle to the pilot case studies, but that led to problems of accessibility and lack of response. Therefore, the two pilot studies provided information that was used in some parts of the analysis as complementary evidence (Yin 1989).

Case studies.

The main case studies were:

i) The Munich Olympic Roofs, Munich, Germany (1972).

The structures belong to the category of saddle-type cable nets.

ii) The Mannheim Garden Centre, Germany (1975).

The structure belongs to the category of domed grid shell structure.

iii) The Munich Aviary, Germany (1975-1980).

The structure belongs to the category of wire net supported on masts.

iv) The King Abdul Aziz University Sports Hall in Jeddah, Saudi Arabia (1979).

The structure is a combination of cable net and tent supported on masts.

v) The diplomatic club in Riyadh, Saudi Arabia (1980).

The structure is a matching of a rigid element, that is a wall, with a stained glass tiled cable net and a fabric tent structure attached to it.

vi) The Olympic Ice Stadium in Calgary, Canada (1981).

The structure belongs to the categories of cable net and concrete shells.

vii) The Schlumberger Research Centre in Cambridge, U. K. (1985).

The structure belongs to the category of tent structures.

The final stage.

During the last stage of data collection two interviews were conducted with two pioneers in the field of unconventional structures. The architect (A) and the engineer (E), who were interviewed at this stage of the research, acted as consultants or principal designers in most, but not all, of the case study projects used here. The interviewees

did not discuss any one building in particular, but focused on the experiences of the design process of unconventional structures in a broad and diverse manner.

The collection of data.

The researcher had useful contacts who played mediating role so that the interviewees could be approached. Letters were sent to them with a brief description of the aim of the study. Thus, as part of her field work, the researcher travelled in Britain and to Germany to meet the interviewees and visit unconventional structures in the period March and December 1992. Also in September 1992, she undertook a trip to Seville and studied the unconventional structures built for Expo'92. It was considered useful to contrast and compare these buildings with the earlier ones chosen for the purposes of the present study.

The trip to Germany took place in November 1992, and included site visits to the four case studies located in Germany. The site visits helped the visualization of their size, scale, detailing and performance. The trip was fruitful and the participants generally cooperative. The use of a dictaphone ensured accuracy in the way reports were monitored. Anonymity was an issue that was discussed before the start of each interview. A number of interviewees supplied the researcher with additional unpublished material and gave her permission to use the material in the thesis. Part of this material consisted of slides of models and plans that had been used in the design process. Transcripts of all the interview tape recordings were produced. Even though these transcripts are an important historical document, it was felt that the issue of anonymity precluded their inclusion as appendices to this thesis.

The analysis of data.

After the data collection, there was a substantial amount of information which the researcher had to analyse.

The choice of method of analysis was influenced by the researcher's aim to retain the richness of the data and meet the objectives of the research, that is to explore the design processes of the chosen unconventional projects, as well as the extent to which they were influenced by the social-working environment in which the design teams operated. Grounded Theory, a qualitative research approach with specific techniques and procedures for analysing data, was adopted by the researcher.

Glaser and Strauss (1967) first proposed the principles of Grounded Theory, which has since been used and adopted by many researchers. Grounded Theory was developed specifically for gaining insight into social phenomena. Glaser (1978) suggests that the reason Grounded Theory works is because it does not force data into boxes or categories that have been deductively derived. Instead the researcher is involved in the process of generating Grounded Theory, the direction of which derives from the categories the respondents themselves use, in order to understand the context of their situation. Thus, Grounded Theory is a process that allows the researcher to generate findings from available data, rather than forcing this data into already defined categories. Therefore, the method is not determining the findings. Instead the emerging data, free from restriction, determine the findings.

The use of Grounded Theory was chosen specifically because of its open approach which is good for dealing with transcripts. In using the interpretations of the informed "social actors" of each of the nine cases, the aim was to gain a clear conceptualization of the design process and the factors most influential or given the most consideration within that process. Thus, the process could be traced and "why" questions could be answered.

The stages leading to the grounding of the theory are the following:

- i. Open Coding: Strauss and Corbin (1990) define open coding as the process of breaking down, examining, comparing, conceptualizing and categorising data. That can happen when an observation, sentence or paragraph is taken apart and each discrete

incident, idea or event is given a name or something that stands for or represents a phenomenon (p.63). In the present study, the “line-by-line” analysis was chosen as the most detailed and generative. The outcome was a list of all phenomena appearing in the respondents’ accounts (see appendix 6).

ii. Axial Coding: The aim of axial coding is to make connections between categories and subcategories, “this is done by utilising a coding paradigm involving conditions, context, action/interactional strategies and consequences” (Strauss and Corbin 1990, p. 99). The researcher has to select a category or phenomenon, the context in which it is embedded, the action/interactional strategies by which it is handled and the consequences of these strategies. There might be a number of categories which are repeatedly present and equally interesting to be further explored. However, it is the researcher’s decision to focus onto the category which concerns him or her more (ibid). The criteria of choosing the core category of the present study were associated with the design process of unconventional structures as a problem solving task, where crucial decisions have to be made.

The interrelation of the main phenomenon and its subcategories can be presented in the form of a “paradigm model” which is the abstract version of the subsequent mini frameworks that emerge from the axial coding of each individual case.

In the present research, the way in which subcategories related to one category are linked is shown in the following figure:

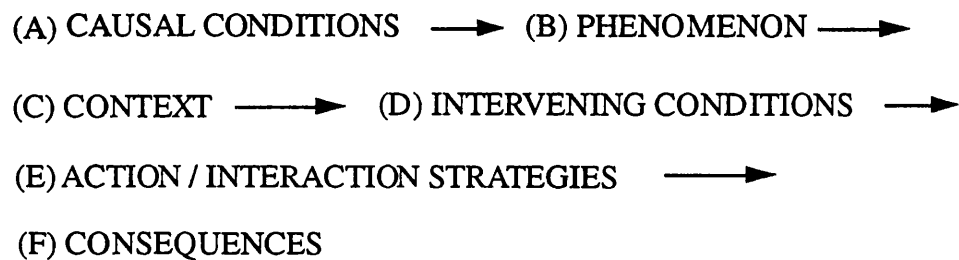


fig. 14. Simplified form of a paradigm model. Source: Strauss and Corbin (1990), p.99. (see also glossary at the end of the present chapter)

The terms in the figure are defined as follows:

Causal conditions: the term is used to describe the events or incidents that led to the occurrence or development of a phenomenon. “Causal conditions are often pointed to in the data by terms such as: “when”, “while”, “since”, “because”, “due to”, “on account of” (ibid, p.101).

Context: the term is used to describe the specific sets of properties that pertain to the phenomenon and can also indicate the particular set of conditions “within which the action/interactional strategies are taken to manage, handle, carry on and respond to a specific phenomenon” (ibid, p.101).

Intervening conditions: these conditions act either to facilitate or constrain the action/interactional strategies and are related to “time, space, culture, economic status, technological status, career, history and individual biography” (ibid, p.103)

Actional-interactional strategies: “They are action oriented verbs or participles” which give suggestions regarding the handling of the phenomenon (ibid, p.105).

Consequences: They are described as the outcome of the proposed action/interactional strategies.

iii. Selective Coding: After the definition of the core category, further relation in terms of a general paradigm has to be attempted. Furthermore, Strauss and Corbin (1990) state that the categories have to be related at a dimensional level. The validation of the categories against data must follow, and, lastly, the incomplete categories must be filled in or may be refined and/or developed, so that the “story line” can be fully explicated.

Integration at this stage is not very different from axial coding. The only difference is that “it is done at a higher more abstract level” (ibid, p. 117). The systematic

development of this stage consists of five main steps. These are: firstly, the explication of the story line; secondly, the relation of subcategories to the core category; thirdly, the relation of categories at a dimensional level; fourthly, the validation of those relationships against data, and fifth, “the filling in of categories that need further refinement and/or development” (ibid, p.118).

For reasons of reliability, two coders, (the researcher and one architecture graduate used as an assistant) were responsible for the coding. The assistant coder was provided with the transcripts and was asked to initially identify the core category and then follow with open and axial coding of the interviews. He was also supplied with some relevant literature material, wherever it was considered necessary. In some cases, this material constituted a point of reference for both coders, which helped them clarify doubts and provided them with a common basis for discussions and disagreements.

Following the Grounded Theory approach, after the selective coding stage, further and intensive reading of the coded interviews occurred so that the core category was selected and refined. The aim was to provide designers with understanding and further insight regarding issues related to the core category. More specifically, the researcher aimed to show how various types of awareness (context) come to constitute conditions for action and reaction, how they are maintained (strategies), how they change (process), and what that means for those involved (consequences).

The data revealed phenomena referred to, over and over again, such as the association of unconventional schemes to the innovation that they initiate. That in turn was linked to the several factors which appeared to create difficulties during the design process.

Thus, at this stage of the research, the first task was to explicate “the story line” and identify the core category. After the first stage of analysis –the identification of the “core” category–, the second stage of the analysis dealt with the juxtaposition of attitudes towards the nature of the design process of unconventional structures.

According to the methodological framework, and in order that the conclusions could be generalisable, the “process” had to be developed.

Strauss and Corbin (1990) define as “process” the “linking of action/interactional sequences”. “This linking of sequences is accomplished by noting: (a) the change in conditions influencing action/interaction over time; (b) the action/interactional response to that change; (c) the consequences that result from that action/interactional response; and finally by (d) describing how those consequences become part of the conditions influencing the next action/interactional sequence. Change can be viewed as the consequence of planned action/interaction or it may occur as a result of contingency, “an unanticipated and unplanned for happening that brings about change in conditions” (p.143). “Process must be accounted for to a degree sufficient to give the reader a sense of flow of events that occur with the passage of time” (p.147).

Glossary

“Axial Coding: A set of procedures whereby data are put back together in new ways after open coding, by making connections between categories. This is done by utilizing a coding paradigm involving conditions, context, action/interactional strategies and consequences.

Causal Conditions: Events, incidents, happenings that lead to the occurrence or development of a phenomenon.

Phenomenon: The central idea, event, happening, incident about which a set of actions or interactions are directed at managing, handling, or to which a set of actions is related.

Context: The specific set of properties that pertain to a phenomenon; that is, the locations of events or incidents pertaining to a phenomenon along a dimensional range. Context represents the particular set of conditions within which the action/interactional strategies are taken.

Intervening Conditions: The structural conditions bearing on action/ interactional strategies that pertain to a phenomenon. They facilitate or constrain the strategies taken within a specific context.

Action/Interaction: Strategies devised to manage, handle, carry out, respond to a phenomenon under a specific set of perceived conditions.

Consequences: Outcomes or results of action and interaction.”

(Strauss and Corbin 1990, p. 96)

Chapter 5. Research procedure, analysis of data and presentation of findings. Phase I.

5.1. Introduction.

This chapter presents the findings of the study of the design process of the two pilot case studies and seven main case studies. The nine cases are presented on an individual basis but using a similar structure. This structure consists of a technical description of each project, the history of the assembly of the design team and a brief presentation of each interview. Finally, there is a brief presentation of the interviews with the architect and the engineer who participated in most of the projects in question.

The pilot studies are described in the first part of this chapter and a discussion on the findings of them follows. The second part of the chapter presents, the main case studies. The third section describes the interviews with the pioneering architect and engineer. The fourth section gives an overall picture of the process and the extent to which it takes account of and influences the strategic issues within the design team. This section consists of the explication of the story line, which is the first attempt at identification of the core category and its links to action/interactional factors. The last part of the chapter presents a table –the paradigm model– summarising the design processes which have been chosen by the nine design teams.

The case studies are presented in chronological order, according to date of construction. Participants' actual names, due to the anonymity issue, are not presented. Instead, AP_n represents the architectural practice to which A_n , the architect interviewee, belonged. " n " is the number of the case study. EP_n represents the engineering practice to which E_n , the engineer interviewee, belonged. P_n denotes the project concerned. $A'n$ or $E'n$ and $A'P_n$ or $E'P_n$ are other architectural or engineering consultants and the consultant practices for whom they worked. LAP_n , $LA'P_n$, LEP_n and $LE'P_n$ refer to the leader of the respective practices.

A and E represent the two pioneers who gave the general interviews.

5.2. Pilot case studies:

5.2.1. Analysis of findings.

The respondent of the first pilot case study was working in the engineering firm responsible for the project while the respondent of the second pilot case study was an architect from the architectural practice responsible. The main purpose of the case studies was to test out the appropriateness of the questions, the technique with which interviews should be carried out and the way the findings should be presented and subsequently analysed. Despite their shortcomings, the findings of these pilot case studies provided valuable information. Therefore, the findings are included in the analysis of data.

Pilot case study 1

P1

The Sydney Opera House, Australia (1957-1973).

Architects: AP1, Structural engineers: EP1.

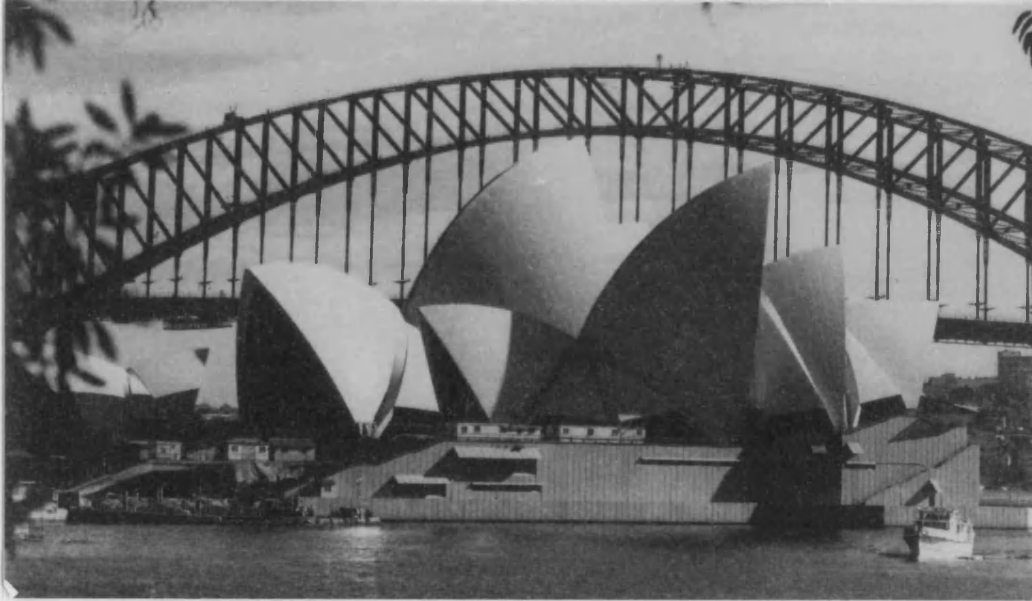


fig. 15. Sydney Opera House. Source A. Holgate (1986) "The Art of Structural Engineering", p. 11.

The Opera House Roof is formed from a series of concrete "shells". The "shells" are formed from a series of hollow precast concrete ribs. The building is undoubtedly a landmark and is associated with Sydney in the same way that the Eiffel Tower is associated with Paris. It was predicted that the project would cost £A7.20 million in 1957 and be completed by January 1963. Eventually, it cost £A102.00 million and was completed in October 1973 (Hall 1980). For the purposes of the present research it was interesting to obtain reassessment of the objective and subjective obstacles that the design process went through. In contrast to the findings of M. Baume's (1967), who felt like giving up when he tried to get an insight into the case by collecting relevant documents, it was hoped that fruitful results could emerge but without the author's personal view on the matter.

History of P1.

P1 was the result of a competition won by a young architect –A1 towards the end of 1950's. A1 then approached EP1, an established engineering practice, in order to realise the building. The interviewee of this case study –E1 was an employee of EP1 who worked on P1 for a period of time.

E1 joined the design group in EP1 working on P1 at a very particular critical point when there had been a history of some two years or more. The substructure had already been designed and built and the superstructure of the roofs was subject to research investigation. Up until that time the direction of the design had been to emulate A1's free-hand drawings using conventional concrete which had not been successful. Subsequently, there was a change in direction in terms of the design of the structural system.

Brief presentation of the interview with E1.

E1 recalled that it took a laborious three months to undertake geometrical constructs. The construction of a computer program to emulate the geometry in order to analyse it structurally was carried out in parallel. However, computer technology was still at a very primitive stage and everything had to be started from scratch. Models were also made by both A1 and EP1.

There was, as E1 observed, not a great deal of communication between architect and engineer. The architects were working individually expecting the outcome of the research undertaken by the engineers. The inaccurate site analysis led to a change of direction in the design half way through the construction phase. The implication on time and cost due to this alteration caused the client a lot of anxiety. Thus, in order to streamline the design process, the design team were doing different things in parallel; such as the analysis and exploratory research in terms of materials and techniques, of contracting and so on. E1 explained that the team would have been better off if they

could have afforded the time to take 'sequential' rather than 'parallel' steps in the design process.

E1 attributed the difficulties encountered during the project to the responsibility of the architects. A1's ideas had not been worked out properly and as a result the information EP1 received from A1 was 'sketchy'. Also E1 believed that A1 underestimated the scale of the project and therefore they did not adjust the size of his team accordingly.

The uncertainty about the design process and lack of role clarity of architects and engineers was vast. Although E1 believed that what happened in P1 would not have been helped by either knowledge or experience, he stresses that A1 should have collaborated with another architect with more experience in this field to meet the "ambitious" scheme. One of the consequences of having A1 carrying out the task on his own was a stressful working environment which proved harmful for the whole team. The biggest problem encountered during the design process of P1, according to E1, was firstly the suppression of intuitive thinking on the part of the group's engineers by extensive calculations. Secondly, the lack of experience of the architectural practice was partly responsible for the difficulties that appeared. Lastly, E1 cited another problem during the design process, with regard to the low flow of the information which caused "irritation". That he attributed to the complex process which he characterised as more difficult and prone to error compared to more conventional cases. E1 compared the use of models to the use of computers. What was made clear from this comparison was the usefulness of physical modelling regarding the understanding and visualisation of complex 3D constructions. With respect to computers he explained their importance in order that accuracy would be achieved but noted also the danger of encouraging the design team to over-rely upon them.

Pilot case study 2

P2

The Institute for Lightweight Structures, Stuttgart Germany (1968).

Design team: AP2.



fig. 16. The Institute of Lightweight Structures in Stuttgart.

An eye-loop connection of the cable net with the mast-supported high points-provides the skeleton (IL17 1978, p. 28). The leader of AP2 used this project as a “demonstration structure” to educate architects and engineers working in AP2. A building that covers an area of 460 square meters with 17 meter mast height was used to research the form. The successful experiment was finally repeated on a bigger scale at the German Pavilion built for the World Exposition in Montreal, Canada 1967. There were no apparent reasons for which the design process would be labelled as problematic. However invention as an end in itself caused difficulties which made the project worth exploring. It is also interesting to note that the Montreal Pavilion would probably not have been executed as successfully if a full-scale model had not preceded the actual building.

History of P2.

Since P2 was conceived as a prototype structure for another project of larger scale to be carried out by AP2, AP2 were both the client and the designer of P2. On top of that AP2 were to occupy the resultant building of P2 as their office. A2 was a young architect at the time and this project was his first experience with unconventional structures. The atmosphere of the design process was relaxed and the objective of the design was experimental and innovative with no immediate time limitations. In the end P2 took two years to realise without overrunning cost.

Brief presentation of the interview with A2.

The challenge for the design team was the chance to free the function of the building from its form and use the design process as a learning experience in designing unconventional details.

A2 saw the leader of AP2 as the dominant individual in the design of P2. A2 was a strong character, well-respected by his group for his awareness, realistic approach, experience and managerial skills.

For purposes of experimentation, the design team felt the need to design everything in an unconventional manner. That was initiated by the leader and every new attempt was a lesson for the group. Because of this, the design of details had to start very early so that the appropriate construction method could be decided on.

A2 explained that during the design of P2 all the means of communication, visualisation and simulation were used to good effect. The design team started with physical models and hand-drawings. Computers came much later in the design process, since at the time there were no user-friendly programs available. A number of lessons were drawn regarding the interaction of these means during the process of P2. Although computers

were not employed extensively in this project, A2, nevertheless, recognised the advantages offered by today's computer technology.

Finally A2 believed that physical modelling and computers must complement one another, but as far as visualisation is concerned, physical modelling remains the best means because of its tactile qualities. A2 explained that the design team of the project was focused on the user satisfaction and utilisation of the large space.

He also argued that users of unconventional structures need to be educated to be able to personalise a space with the qualities of P2.

Commenting on the changing roles of architects and engineers A2 believed that the these two professions are becoming more interchangeable. That, as he explained, is attributed to the dual nature of the current projects.

According to A2, the lessons to be drawn out of P2 was one of education.

Pilot case studies: Conclusion.

The above findings were obtained after observing and analysing 'line-by-line' the entire transcript of the pilot case studies' interviews. From these findings the following suggestions emerged and changes were made in order to improve the interviewing procedure and techniques used in the main case studies:

i) The respondents of the two pilot case studies focused on different aspects of the respective projects. A2's accounts concentrated on his concern of user satisfaction and utilisation of space, whereas E1's accounts emphasised technical issues and the organisation of the team. It, therefore, seemed logical for the main case studies to interview representatives from both disciplines, architects and engineers.

ii) In the first pilot study, the interviewee was not only a junior member of the design team at the time, but was also involved in P1 for a relatively short period of time. (However, this particular project was executed in the 1950's, and therefore it was found difficult to find living senior members for interviews.). It was thus decided that the interviews for the main case studies would be carried out with key-members of the design team whenever possible.

iii) Many issues relating to the structure of the group were raised by the two pilot case studies. For example, issues related to leadership, role clarity, biographical characteristics of individuals comprising the group (education, age, experience) appeared to be of particular importance. As a result, special attention was given to qualitative questions regarding the organisation of the groups.

iv) After completing the pilot case studies, it was decided that the set of questions should be an open-ended part of the interview guide. This was because respondents tended to offer more elaborate answers than the questions suggested. This made it difficult to follow strictly the sequence of the questions and provide the researcher with extra, but valuable material. In short, respondents would be given more freedom, they

would feel more relaxed to expand on their answers, and open up unexpected, but interesting, topics.

5.3. Main cases studies.

The choice of the seven main case studies was determined, as described in the methodology chapter, by the desire to find a representative building of a number of categories into which unconventional structures fall. The respondents were, as described earlier, senior designers who participated actively in the design process of the respective buildings. After the improvements which the pilot studies suggested, an interview guide was used (see Appendix 2) to lead the conversation between the researcher and the respondents.

P3

The Stadium for the Munich Olympics, Germany (1972).

Architects: AP3.

Consultant architects: A P3.

Structural engineers: EP3.



fig. 17. The Munich Olympic Roofs.

It was described by the design team as “nine units saddle-type nets with two suspension points, two under stayed support points, four anchor points per unit, and one continuous frontal edge cable for all units” (IL17 1978, p.30). Architects AP3 won the competition but managed to complete it only with A P3’s contribution. The history of the project is a very good example of political intervention and tension between architect and engineer (Holgate 1986, p. 100).

History of P3.

P3 was the result of a competition won by AP3 with a scheme involving a lightweight structure which they could not realise. AP3 then approached A'P3, who were specialists in the field of lightweight structures. EP3 had been working with AP3 from the beginning. After the preliminary design stage of the revised scheme A'P3 stepped down due to disagreements and differences of opinion with the rest of the team. P3 was realised without further input from A'P3.

A'3 was interviewed, instead of a member of AP3, on the basis that it was A'P3 who came up with the final solution. Although he was not the leader of the team, he was a senior member from A'P3 and was responsible for a large proportion of the work. E3 was also a senior member from EP3 even though he was not the leader of EP3.

Brief presentation of the interview with A'3.

A'3 was very critical towards the approach adopted by the competition-winning architect (A3) concerning unconventional structural aspects of the project. As he explained, A3 had focused on the aesthetics and not on the combination of the form and the way to realise it. A'3 discussed the best means of visualising the structural behaviour. He elaborated on the tactile qualities of physical modelling versus computer programs. A'3 had particular views about the relationship between physical models and computer models. More specifically, as he stressed, computers must follow physical modelling which can inform the design team and give the necessary 'input' to the computers.

Having previous experience in the field of unconventional structures to back up their efforts, A'P3 approached the design "step-by-step". Yet throughout the design process, issues concerning detail and construction were considered at the earliest instant possible. The point was that architects were working on drawings which they then

presented to the engineers who in turn would judge the feasibility of the proposals through calculations.

A'3 also stressed the importance of understanding certain critical production methods of materials, for example, cables and roof cladding. However, for the rest of the design team, this was a completely new field and they approached the design with, according to A'3, unnecessary caution which led to an over-designed structure.

A'3 strongly believed that experience, related to background and training, plays an important role in the design of unconventional structures. He stressed that it is important for designers to realise that the field of unconventional structures does not follow the conventional principles of stiffness.

A'3 went on to suggest that knowledge in this field could not be taught within classical architectural studies, but only learnt through experience from working with experts. The critical point, which illustrates the necessity of knowledge is that “there must be co-operation and agreement between the shape and the structural behaviour”.

Not only were there disagreements between LAP3 (the leader of AP3) and A'P3 arising from a different way of thinking, but disagreements also occurred between A'P3, EP3 and the contractor regarding the “heaviness” of the roof and the growing size of the design group. The growing size imposed the creation of smaller groups that had very little connection between them. A'3 explained that this had an impact on the communication between the members of the design team.

A'3 said that the biggest difficulty during the design which was convincing the client and the proof engineer that the structure was feasible. Nevertheless A'3 saw P3 as a successful building, except from some insignificant defects. A'3 reiterated the point regarding the importance of experience when asked to pinpoint the lessons to be learnt from this project. He explained that by having “know-how” available at the early stages of the design, fewer mistakes are likely to occur. He also suggested that research

should stop when erection starts. Lastly, he stated that each new building must be a continuation and improvement of technology and ideas applied in precedent buildings.

Brief presentation of the interview with E3.

The buildability of P3 –a competition winning scheme– was doubted after the preliminary design phase, when the engineers were invited to help the architects. Soon the consultant architect, who was also invited to offer his expertise, left the design team due to disagreements. E3 identified LA P3 as being the dominant member of the design team and indirectly cited that this was the source of disagreement which led to the subsequent departure of A P3. He also explained that the major difference between LA P3 and EP3 was that the approach of the former was “empirical” whereas that of the latter was “based on theories”.

E3 stated that A P3’s previous experience was in fact irrelevant for the needs of P3. The structures that had been formerly designed by A P3 were, he believed, far smaller than P3, and that made it impossible for the same techniques of simulation to be employed.

E3 also disagreed with A P3 on the issue of communication means, visualisation and simulation. A P3 believed that models were efficient and reliable for simulation, whereas the engineers favoured computer programs, which they considered as less time-consuming and more accurate. This accuracy would prevent overdesigning of the structure and, therefore, better adjustment on site. As a result, the design team made physical models to evaluate stresses and deflections. Computer programs, were also developed in parallel. Nowadays, according to E3, visualisation can be achieved with computers due to the improvement in computer software and hardware but, nevertheless, physical models are still necessary for testing details.

Nevertheless, E3 felt that the design team worked very closely together from the beginning, even though this was the first time that they had collaborated on a project.

There were minor disagreements, he said, which never went beyond the normal disputes one would usually expect in any design team. He also stressed the genuine and unique experience he had working with all the other disciplines at the same time and place.

E3 specifically pointed out his relationship with A'P3 throughout the design process, which, despite several disagreements, was always constructive and fruitful. The client's participation in the design process was passive and the only restriction he imposed was a limited budget. However, soon after the first financial difficulties appeared, he and everyone else accepted that that had been an unrealistic figure.

Since the completion of P3, EP3 has since designed several more similar structures. However, E3 felt that LA'P3's experience undoubtedly raised the design team's confidence. The group developed the tools to design unconventionally, and their knowledge of new materials increased.

E3's belief in the importance of detailing in unconventional structures was highlighted. Emphasis was placed not on some qualities of detailing, such as the sizing of elements, but on the manner of assembling these elements. This was also reflected in the contractor's involvement in the design of the details.

E3 explained that the engineers were dominant because the structure of P3 was of an engineering nature, which made it difficult for the architects to grasp. That was related to the conventional way in which architects try to hide the structure within the form of the building. A further implication of this difficulty was that it was hard for them to participate in the decision on material to be employed.

In general, though, E3 believed that in unconventional structures the relationship between architects and engineers is an equal one. Unlike normal buildings, where architects are responsible for most of the major decisions, in unconventional structures,

the dominance of the structure makes the engineer more powerful and his or her input more necessary for a successful and feasible outcome to be achieved.

Based on E3's accounts, it appears that the building was successful both architecturally and structurally. E3 placed particular emphasis on the pioneering ideas involved in the design such as the design of cables and foundations as well as the contribution to the national codes which were later used in many other structures.

The main lesson to be learnt from this particular experience was the communication between architects and engineers. E3 believed that the education of architects was needed to incorporate the basic knowledge of structural design. He also suggested that architects must realise that they no longer play the same dominant role they used to play in the design process of conventional structures.

Summary.

Both accounts were critical of the “unbuildability” of the competition winning scheme produced by A3. In his account, E3 was also critical of the way LA P3 became dominant within the design team. This, in E3's opinion, was the main cause of disagreements. He further distinguished the methods employed by LA P3 as “empirical” from his approach which was based on “theories”.

E3 disagreed with A3's emphasis on the importance of LA P3's previous experience on this type of structure because P3 was of a much larger scale than the structures LA P3 had previously been involved with. They also disagreed of appropriate means of communication. While LA P3 believed that computers should only be used to complement physical modelling, E3 viewed the use of computers as more constructive than the use of physical models.

It is interesting to note that E3 did not think that the disagreements with A P3 caused major problems in the design process or their working relationships. He further pointed

out that EP3 had subsequently completed several other successful structures in collaboration with AP3.

Finally, A'3 and E3 offered different opinions regarding the education of young designers. A'3 believed that the design of unconventional structures cannot be taught in general. The most important thing is to learn through experience the interdependence of the shape and the structural behaviour of the structure. E3 thought it vital that architects' education should incorporate the basic knowledge of structural design and that architects should recognise the increasing importance of the engineer's role in the design team.

P4

The Mannheim Garden Centre, Germany (1975).

Architects: AP4.

Consultant architects: A P4.

Structural engineers for the ground and concrete works: EP4.

Structural engineers for the roof and roof supporting structures: E P4.



fig. 18. The Mannheim Garden Centre.

It is described by A P4 as a domed shell structure produced by deformation of a plane lattice grid. Its bendable members are doubled over larger spans, with loose joints tightened for final stabilisation, reinforced by diagonally superimposed cable net (IL17 p. 60, 1978). It is a good example of how simplicity of the concept can be misleading when it comes to realisation and construction (IL17 1978).

History of P4.

P4 was a competition scheme won by AP4, a local architectural firm. The client of P4, a public building intended for a garden exhibition, was the local city council. AP4, having found that they could not realise the competition winning scheme, approached A'P4 for help. A'P4 then introduced E'P4 into the design team to replace the original engineers, who were unable to execute unconventional structures. Both E'P4 and A'P4 were experienced in the field of unconventional structures. Shortly after their appointment, A'P4 proposed an entirely new scheme which was immediately approved by all members of the design team. This was the scheme that was eventually realised. However, by the time E'P4 was involved, several decisions about the structure had already been made; these included the form (ground plan) of the building, the material of the structure –timber in this case, and also the dimensions of the timber section for the structure. Both the interviewees A'4 and E'4 were senior members of the respective consulting teams.

Brief presentation of the interview with A'4.

A'4 started with comments on the working relationship with A4 which was positive. Several alternatives were discussed but discarded in favour of the final solution purely because of 'arbitrary' reasons. That is to say, the scheme was proposed for the sake of exploration of an inverted shape of the hanging net. Although both A'P4 and E'P4 were experienced in this field they had never realised a structure of this scale. Therefore, it was extremely difficult to make any realistic estimation of the cost of the structure.

A'4 went on to confirm that previous experience not only would have helped the cost estimate but would have also facilitated the design and construction of the project. In this case it was decided that cost would be of secondary importance. Also, the time factor was not critical. After making an early start, the team encountered difficulties

with modelling techniques. These concerned the size and the complexity of the model, combined with the difficulty in handling the material from which the model was made.

The involvement of the engineer who worked on the original scheme, was seen unfavourably by A'4. Due to their lack of experience in this field, they were unable to work in sequence with the architect. The architects believed that they could elaborate and advance without the aid of engineers. E'P4 was then invited to bridge the gap which had been created between the project architects and the initially appointed engineers. The newly approached engineers soon discovered that the original provision for the structure had to be increased in order to cover the required span.

Although A'4 had previously mentioned that cost was not a significant criterion for the design, he added that it had been difficult to convince the client that because of changes and additions made to the structure on site, the budget had to be increased. What happened was that the stiffness of the elements initially designated were not sufficient to prevent collapse due to buckling.

The design team used various means for visualisation, communication and simulation, such as models at the early stages and computers at later ones. At that time, computer technology was still at a relatively embryonic stage and was not widely available. Nevertheless, E'4 recognised the advantage of computers over the traditional techniques of using physical models.

A'4 had very strong opinions on the different roles that architects and structural engineers play regarding unconventional structures. He argued that the engineer is the one who is going to turn an idea into a shape by understanding the forces acting upon that shape, with the ultimate target being that of achieving an economical and elegant structural solution.

The point made by A'4 was that whereas in conventional structures the engineer's role is usually to interpret the form of the building given by the architect in structural terms,

unconventional structures require a mutual understanding of the relationship between form and structure by both parties. In other words, the architect needs to possess a certain amount of knowledge of unconventional structural behaviour in order to cooperate with the engineer in developing the form. A'4 strongly believed that the effect of this cooperation ought to be evident by simply observing a building. Even though he felt that such an effect was reflected in the 'architecture' of the building of P4, he regretted the fact that it was not immediately apparent to the casual observer.

Although in A'4's words the proof engineer 'was very developed in his thinking', due to the unfamiliar nature of the project, it was extremely difficult to verify E'P4's calculations. At the end, the proof engineer came up with the idea of physically simulating the effect of snow load on the structure. This was done by observing the deflection caused by suspending garbage bins filled with water on the structure. The deflection measurement was conducted by a photogrammeter, and the deviation of the calculation from the real deflection was only about 2mm in 65mm.

Apparently, members of the design team enjoyed a particularly good working relationship. This, according to A'4, was the result of working in a group of manageable size consisting of 'co-operative' members.

Once again, A'4 stressed the importance of the architect's understanding of structural behaviour in the design of unconventional structures. Further, he saw engineers' 'obsession' with calculations to be a hindrance to the design process. Indeed, he cited that the main lesson to be learnt from this experience is that architects and engineers designing unconventional structures have to free themselves from norms. This type of understanding comes from experience, observing and "looking around at the things that have been done by other people".

Lastly, A'4 repeated that the most significant problem of the design process is linked to the working relationship that develops within a group.

Brief presentation of the interview with E'4.

E'4 not only recognised the necessity of the proof-engineer's role but also understood the difficulties in verifying the feasibility of the proposed structure due to its unconventional nature. Unlike conventional structures, there seemed to be no established standards of codes for these structures and students at the university were not taught how to do the various and necessary calculations. That was a time-consuming and ambiguous process. The situation in which the proof engineer found himself was very difficult. The means to prove the feasibility were limited and the computer programs available at the time were expensive. These factors forced them to rely upon their own judgment .

At the end, as mentioned in A'4's accounts, the structure's feasibility was verified by actually load testing the structure. E'4 later thought that it had been a brave and honest decision on the proof engineer's part to ask for that load test to be carried out.

E'4 could sense the uncertainties of other members of the design team although these uncertainties were not communicated among them. The strong personality of E'4's superior contributed to overcoming this anxiety. E'4 recalled that the controlling criteria were not the cost of the design but rather the pressure of time.

In E'4's accounts, disagreements could be related to the uncertainty of the participants, which could easily have led them to diffuse their responsibility. E'4 felt that the relatively late involvement of E'P4 excluded them from certain disagreements but, on the other hand, thought that E'P4 could have influenced the structure more positively if they had also taken part in these disagreements.

Both physical and computer models were used as design tools in P4. E'4 pointed out that both of these had drawbacks even though the results from these two types of models were very similar. As he explained, while the computer model has its limitations related to the 'power of the machine' and 'lack of graphical output', the physical model could collapse And be destroyed in structural tests. E'4 also pointed out

another potential shortcoming of undertaking structural testing on physical models. That, as he explained, is the difficulty designers face when attempting to scale up results from a model to full scale.

Nevertheless, E'4 believed that both types of models should be employed in the design of unconventional structures regardless of the advances in computing technology in the past few decades. Even though E'4 saw the design of details as the responsibility of the engineers, he also pointed out the reluctance of the architects to participate.

E'4's criterion for judging the success of the building, was the adoption of a similar idea in other contemporary buildings. E'4 had an interesting theory regarding risk taking. The fact that the design team were not able to understand the real danger of buckling encouraged them to take risks and proceed with its construction.

The design team was anxious about their reputation should things go wrong but finally trust enabled the design team to carry it through.

E'4 cited the lessons from P4 as technological ones, mentioning particularly the understanding of the structural behaviour of unconventional structures. There were two other points which E'4 made as further lessons to be learnt from the design of P4. The first one concerned the issues of communication between members of the design team and the second concerned individuals within the design team. The design of P4 should be taken in the future as a blue-print for grid-shells design. The second point was expanded later on in E'4's accounts. It was explained that individuality has to be maintained and that the success of the team depends upon a group of "good" individuals.

Referring to the roles of architects and engineers involved in the design of unconventional structures, E'4 raised several interesting points regarding the educational background and approach of designers. These concerned the difficulties a conventionally educated architect or engineer would encounter when designing an

unconventional structure. He suggested that the designer of unconventional structures has to familiarise himself or herself with the special issues that govern their design.

E'4 believed that the distinction between architecture and engineering varies amongst different cultural backgrounds. At the end of his account E'4 offered a wide range of advice to young designers in this field. He highlighted the importance of choosing the correct person to work with. He also pointed out the importance that existing knowledge and precedents have. Lastly, E'4 explained the advantages that young engineers have over established ones in terms of the expectation of rewards versus efforts.

The danger of being misled by various means of visualisation was additionally mentioned. It was explained that in conventional structures the 'jump' from drawings to real buildings is easy, whereas with unconventional buildings this is much more difficult. It is also important, as E'4 emphasised, that the designer understands correctly not only the argument for an unconventional structure, but also the risks involved in the design of unconventional structures, with regard to the structural safety, which however should not lead to overengineered structures.

Finally, E'4 reinforced a point he had made earlier about the compatibility of individuals and the complementarity of needs as vital characteristics of an effective team.

Summary.

According to both accounts there was a good working relationships between the members of the design team. A'4 attributed this to a design team of manageable size with co-operative members. This also corresponds to what E'4, in his account, termed compatibility of individuals and complementarity of needs. However, A'4 regarded the inexperience of the original engineers as a hindrance to the design process. Although E'P4 had not joined the design team at the time and, therefore, was not involved in the

conflict, E'4 believed that E'P4 would have contributed positively towards the discussions during the early stage of the design process.

Both A'4 and E'4 described the role of the proof engineer in their accounts. E'4 not only sympathised with the difficult task of the proof engineer, but also regarded his decision to verify the structure using physical simulation as a brave and honest one.

Although A'4 did not think that the issues of time and cost limits play a crucial role during the design process, E'4 felt that the pressure of time was a controlling factor.

Both interviewees had strong but dissimilar views on the roles of architects and engineers in the design of unconventional structures. While A'4 emphasised specifically the importance in the understanding of the interrelationship between the form of an unconventional structures and their structural behaviours, E'4 stressed the necessity not only for familiarisation with the special issues that govern the design of unconventional structures, but also for understanding the arguments for and against taking the risk involved in building unconventional structures.

Regarding the lessons learned from this experience and advice to young designers involved in the design of unconventional structures, both interviewees stated, amongst other points, the importance of making use of existing knowledge by observing and understanding precedent buildings.

P5

The King Abdul Aziz University Sports Hall in Jeddah, Saudi Arabia (1979).

Architects: AP5.

Collaborating architect: A P5.

Structural engineers: EP5.

Concrete works: E P5.



fig. 19. The Jeddah Sports Centre. Source Patterns 5 (1989), Buro Happold Office Literature, p. 40.

The metaphor is of a Bedouin tent as a sports hall. The Jeddah Sports Centre is a combination of cable net and fabric supported on masts. This generated genuine problems with its environmental behaviour, which were, however, solved in an intelligent manner. The design of its mast heads is the key detail that controls the building's structural and environmental issues (Pugh 1989). According to its designers the building could have been more beautiful if more money had been available and the building executed the way it was originally designed.

History of P5.

The client of P5 was the University of King Abdul Aziz which assembled the brief, asking for a sports hall with a village attached to it. However, the limited budget only allowed for the execution of the sports hall. The client did not express any particular ideas and the form of a tent structure was proposed by the chief architect of AP5, a small architectural practice specialising in tent structures. A'P5, another architectural practice, to which A'5 belonged, was then invited by AP5 to collaborate in order to meet the needs of the sizable project, even though the practice had no previous experience in lightweight structures. AP5 after discussions with the client recommended EP5 as structural engineers who were specialists in the field. Previous cooperation between A'P5 and EP5 ensured a successful collaboration. On the contrary, AP5 and A'P5 communicated with difficulty due to the crystallised and rigid ideas of the leader of AP5. Although the final building was the largest tent ever produced and its design initiated genuine details, the designers explained that the tent could have been more successful if the entire brief had been executed and if there had been more resources for additional architectural devices for the tent.

Brief presentation of the interview with A'5.

It was the first time that A'P5 had participated in the design process of an unconventional structure. A'5's interview was not particularly informative which is probably because he participated very little in the decision making process. Even though A'5 estimated that there was an equal contribution from both AP5 and A'P5 in terms of effort, it seemed that A'P5 was in effect merely asked to offer 'more hands' in order to meet the deadline. Although the practices involved in this project had collaborated in the past, A'5 did not believe that this would necessarily guarantee success.

At the beginning of his accounts, A'5 recalled a special relationship between the client and LAP5. The decision that a tent was the answer for the area, according to A'5, was partly because LAP5 never wanted a secure and conservative design. By the time A'5 joined the design team, the form of the tent which was A5's original "spoken idea" had already been designed. According to A'5, this idea of the form was developed by the architects all the way until the end without any opportunities for variations, while EP5 worked on the engineering and detailing of the structure. This was partly due to the time restriction and partly due to the dominant role of LAP5. A'5 spoke of the experience as a peculiar one similar to "going to school", with LAP5 as the professor and the rest as students. This, in A'5's opinion, was consistent with LAP5's style. Additionally, A'5 found it difficult to convince LAP5 of the value of the design work produced by his office. They disagreed particularly on the subject of the material of the roof covering.

Time, for A'5, was an important issue during the design process. A'5 found the geographical distance between the designers' location and that of the site, as well as the cultural differences amongst participants and between client and design team, contributed to this to some extent. More importantly, this was due to the knock-on effect caused by the cost restriction. The design had to be done a second time in order to bring the cost down to within the client's budget. This resulted in the exclusion of the village proposed in the first design. Although the team began designing details relatively early on, the details, most of which were non-standardised, they had to be changed because the contractor had a very different way of thinking.

Other difficulties A'5 encountered during the design process included the design of the peaks, the design of the environmental system and the design of openings for access and windows due to the softness of the tent and the absence of frames. A'5 also recalled that the design team underestimated the effect of sand covering the roof, caused by sandstorms.

A'5 recalled only the presentation model made to show the client at the end of the design process and the mock-up built on site before construction began. He also commented that the use of computers would be beneficial only if one understood precisely what one could obtain from them.

A'5 saw the building as only 90% successful because of the lack of architectural elements. This was partly due to the material finally chosen for the roof covering, and partly due to the exclusion of the village which would have provided a “sequence of steps” architecturally to bring “a large tent in the middle of nowhere” to the human scale.

A'5's experience can be appropriately summed up by his comment on the communication between the design team members using a common language –the language of LAP5. Although he described the experience as fun, he did not wish to repeat it. However, he would like to collaborate with EP5 whom he considered to be sensitive engineers.

Brief presentation of the interview with E5.

E5's detailed accounts of the design process covered many technical and architectural issues. E5 recalled very clearly EP5's involvement in the early discussions on the form of the structure. E5 believed the fact that AP5 and EP5 had previously collaborated in other projects prior to P5 helped to establish the good communication which existed between the members of the design team. E5 also believed that previous experiences were useful even though P5 incorporated the largest scale tent of its time.

E5 saw LAP5 as the leader of the design team who initially designed the structure which was a tension structure reminiscent of the Bedouin tent form. E5 confirmed that the first proposal was for a sports stadium with a village attached to it. This turned out to be too expensive for the client's budget (UK£16m). The second proposal (UK£5m), together with reappraisals of the structural and cladding systems, which excluded much

provisions for the village, finally met with the client's approval. This proposal also excluded a lot of the architectural finishes. As a result, the contribution required from A'5 was drastically reduced.

E5 regarded these cost-cutting measures as mistakes and believed that the building in the original proposal could have been much more majestic with all the architectural devices embellishing the structure. Also, the building would adapt to the landscape with the village attached to it, providing the grading from the human scale to the large scale of the tents. The redesign created some strain on the time restriction which was approximately three years. Lastly, the resultant basic architectural devices also highlighted the difficulties in achieving a truly sympathetic integration between the rigid enclosed spaces (included structures such as seating, changing rooms, teaching blocks, gyms, etc.) and the enclosing space of the tent.

E5 identified some of the environmental issues of the design as the most significant problems encountered during the design process. The design team recognised that the design of the roof covering had to cope with potential hazards caused by sandstorms. E5 disagreed with A'5 on the choice of materials for the roof covering but this was resolved very early on during the design process and a collective decision to use A'5's idea of fabric covering was made after considerations on economy, availability, durability and strength. However, the design of details was delayed due to the late decision to use a double membrane. Some of these details were standardised components mass-produced with existing technology but in quite sophisticated ways. There were also non-standardised components and some difficult details which required innovative solution. Nevertheless, they were, in E5's opinion, relatively basic in strictly architectural and constructional terms. According to E5, all the details were proposed by the design team and improved upon by the contractor and were then worked out during construction and prefabrication.

E5 recalled that the duration of the construction period was around ten weeks including shipping. Six weeks were needed for the erection of the cable net and two for the fabric roof covering. The whole operation from loading the components in Europe ready for shipment to the erection procedures were very carefully worked out in advance. This was highlighted by E5 as one of the triumphs of the project. Nevertheless, E5 regretted that there was not sufficient time to model the building physically. According to E5, the architecture of P5 was rather “stiff” as a result.

Models were used extensively throughout the design process. E5 recalled a sequence of at least five models. Even though many drawings were also produced, the models were used in general as the basis for the difficult communication and more specifically for testing and form-finding. The engineers also carried out hand calculations and computers were used for calculations, testing and visualising the geometry of the structure. E5 thought that the latter task was fulfilled by the computer fairly well, due to the simple form and its repetitive rhythm. E5 believed that CAD technologies nowadays could replace some physical modelling, especially at the beginning of the design process.

Despite the shortcomings previously mentioned, E5 thought that the structure was wonderful and extremely well-built by the contractors. It was particularly successful in combining the traditional nomadic tent form with innovative technologies, of which EP5 was very proud. With hindsight, E5 would have liked to build the structure differently. This, E5 believed, was inevitable because more knowledge had become available.

Summary.

The two interviewees’ –accounts of P5 are quite similar with regard to the development of the design. However, E5 gave a more detailed and informative description of the design process than the brief report by A’5. This is probably because of A’5’s

relatively limited involvement in the design process. This made it very difficult to carry out constructive comparison between the two accounts.

Even though both interviewees regarded LAP5 as the dominant member of the design team, they reacted very differently. Unlike E5, who respected LAP5's knowledge and abilities in this field and enjoyed a good working relationship with the whole team, A'5 saw the over-dominance of LAP5 as counter-productive because it restricted his initiative.

A'5 recalled in his accounts only the model produced at the end of the design process for presentation purposes. He did not mention the other models used for testing, form-finding and visualisation purposes mentioned in E5's accounts. Neither did A'5 regard P5 as a success as much as E5. Both of these points, again, can be explained by A'5's relatively small role in the design team.

P6

The Munich Aviary, Germany (1975-1980).

Architects: AP6.

Consultant architect: A P6.

Structural engineers: EP6.



fig. 20. The Munich Aviary.

The 4500 square metre aviary is formed from a woven wire mesh supported on masts. It is intended for free-flight birds and is a good example, known for its structural efficiency and capacity. The double curvature of the mesh was introduced by changing the relative angle between the two directions of the mesh. Snow loading was the design team's main concern. This was however overcome with the structural solution itself (Dickson 1989, p 29).

History of P6.

The client of P6 approached A6 for the design of the Aviary because A6 had previous experience in zoo architecture. His brief, which required a 'walk-through' aviary, was simple. A6's idea was to have a minimal structure which would be easily adapted to the landscape and friendly to the users –the birds. Almost at the beginning of the project, A6 introduced A P6 as consultant architects who then introduced EP6 as structural engineers. This was the first time that these three partners had worked together as a team, but A P6 and EP6 had collaborated on other projects, especially in the field of unconventional structures.

It was then decided that the aviary should be made of a stainless steel wire mesh structure. Because of the novelty of the structure the restrictive original budget had to be increased. The contractor worked very closely with the design team. There was no strict time limit for the project which, at the end, took four years to complete. A6 was interviewed because he was the principal architect who came up with the original idea. E6, a partner in EP6 involved with the project, was interviewed and gave a detailed technical account of P6.

Brief presentation of the interview with A6.

A6 described his original idea as a big spider net between trees. He imagined the structure as a cloud and wanted it to be as light as possible so that it would adapt to the landscape. A6 admitted his lack of experience in lightweight structures but, as he pointed out, his previous experience in zoo architecture was valuable.

Both A P6 and EP6 were invited to join the design team at the beginning of the design process due to their experience in lightweight structures. A6 believed that without any one of them, P6 would never have been realised, although A6 was particularly perceptive about minor difficulties caused by cultural differences between the multi-national design team. Nevertheless, he admired the engineers' abilities and enjoyed the

experience of collaborating with them which he described as beautiful, despite many minor disagreements during the development of the design. However, A6 expressed that he did not enjoy working with LA P6 who was arrogant and self-important.

A6 was grateful that the project had no specific time restriction because a great deal of time (two years) was spent persuading the local authorities to accept a tent-like structure for the aviary. According to A6's account, the local authorities and architects "aggressively" resisted the idea of a tent. This was not only because of their lack of understanding of unconventional architecture, but also, perhaps more importantly, because of their inappropriate association of the proposed structure with another tent structure constructed nearby in the same valley.

A6 explained how he came up with the idea of using a stainless steel mesh instead of LA P6's cable net idea. According to A6, LA P6 was initially reluctant to accept this idea which was eventually adopted after some testing.

According to A6, the initial cost estimation of DM 2.5m was exceeded and the final cost was around DM 3.8m. This was mainly because of the lack of experience of the design team in this type of structure with an unproven material. The lack of precedents also made it difficult for any accurate cost estimations. Moreover, the lack of technical references made the calculations of snow load extremely difficult.

There was a very clear differentiation of roles between the members of the design team. A6 explained that the engineers were responsible for structural calculations and detailing the structure, in conjunction with the consultant architect. A6 dealt with the authorities and the general layout of the whole aviary, etc. A6 regarded the contractors as part of the design team and valued their contribution very much. The contractors had previously worked with both A P6 and EP6 on other projects. The final cost of the structure, according to A6, would have been much higher without the help of the contractors.

Numerous models were used from the beginning of the design process as the principal means of communication and simulation while hand drawings were very rarely used. Due to the complexity of the structure, this was seen to be the best means of visualisation although, as A6 pointed out, it has the same inherent problems of scaling as drawings. Computers were only used to do calculations. In his accounts, A6 mentioned a test structure which tested snow loads on site over a period of two years.

The design of details, which started two years into the design process, caused many problems. A6 described every detail as a problem. A6 mentioned the difficulties caused by the boundary conditions in particular, which was eventually solved by EP6 in conjunction with a local engineer. There were also difficulties caused by the client's wish to retain an ash tree on the site, the solution to which came from A'6. There were, on the other hand, very few problems encountered during construction. The structure was realised exactly according to the engineers' predictions.

A6 was 'astonished' by the results of P6 mainly because of lack of experience in this field. He also explained that even the engineers, who were experienced, were 'astonished' by the innovation the building had achieved. He described the structure as 'a perfect structure from a human thinking and material view point'. Although he did not see any opportunities, A6 claimed that he would like to do it again and would use the same techniques. A6 was delighted with the result and has since been convinced that it is possible to materialise any imaginative idea. Hence, the advice A6 would give to young designers involved in unconventional structures is the need to be persistent and have faith and enthusiasm in pursuing an idea, even if it means resisting other members of the design team.

However, with hindsight, A6 felt that the problems encountered were typical for the design of such an innovative structure. With the successful completion of the project, most of the anxiety and stress generated within the design team were justified.

AP6 and EP6 collaborated again to produce another similar building in the USA after this experience. EP6 also carried out a further similar project in the Far East.

Brief presentation of the interview with E6.

At the beginning of his accounts, E6 clearly described the rationale behind the appointments of AP6 and EP6. He then recalled that there were many other specialised disciplines involved in the design process. This was because of the different specialised technical issues, which included the use of a new material for building purposes, that needed to be resolved. E6 also recalled a very clear definition of tasks between the members of the design team –demonstrating role clarity consistent with the conventional objectives attached to each discipline. Most of these specialists, according to A6, were engineers and included the client's technical director, the client's veterinary, form-finding specialists, welding specialists, stainless steel specialists, the proof-engineer, welding specialists employed by the subcontractor and building erection specialists.

E6 explained that the client's requirement was simply a 'walk-through' aviary. The engineers were not involved in the development of the brief which was the result of long discussions between the architect, the technical director of the zoo and experts on bird flight. The brief called for the lightest possible enclosure which was sympathetic to the surrounding landscape and able to exclude certain ecological species. This, in general, remained unchanged and well understood by the design team throughout the design process. As a result, the finished building closely resembles the original conceptual model made by A6. E6 strongly believed that P6 was a success.

According to E6, there was no time restriction on the design of P6 which was developed within own time-frame. It took four years in total with the construction period taking a total of seven months this consisting of two periods of about three months each with a six-month gap, because one of the contractors went bankrupt

during the construction period. The effort to preserve the ash tree also caused some delay in the design process.

E6 recalled a budget of DM 2.2 m which was determined at the beginning of the project. He also reported that the design team did not overrun cost. He broke down the costs of the budget into one-third spent on landscaping and two-thirds on structure.

E6 clearly described the design process in his accounts. He reported that the working relationship amongst all three parties was one of the best examples of co-operations he had ever known. E6 did not recall any major disagreements between the members of the design team, but mentioned that there were difficulties in convincing others over the use of the new material and minor disagreements over the solution to preserve the ash tree. Contrary to the experience of A6, E6 found the working relationship with LA P6 to be constructive. E6 explained that a short-hand communication technique had developed between EP6 and A P6 as a result of their previous experiences involving similar structures. E6 valued the contributions made by all the members of the design team in solving the problems in their own ways.

The building material, heavily galvanised steel mast and stainless steel mesh, was chosen by the engineers relatively early on in the design process, because of the requirements for low maintenance costs and effective corrosion resistance. The final form was influenced by the structural behaviour of the material. The success of this building, according to E6, lay mainly in the exploration of a new language necessitated by the use of stainless steel mesh as a new building material. E6 explained that it was the most minimal material possible to realise the building. Nevertheless, the decision on the use of this new material was initially met with doubts and scepticism from LA P6 and the client.

The design of details began as soon as the solution to preserve the ash tree was chosen. Both standardised and non-standardised components were used. The details were proposed by the design team, who saw it as a challenge, with valuable input from the

contractors and fabricators. The design team were particularly concerned with the method of erection. They put in a considerable amount of work to model the process. According to E6, the contractor made a physical model to understand the process while the engineers carried out calculations and 'numerical erections' on the computer which was very time consuming but a 'truly inventive piece of engineering'. The structure was eventually erected very much as anticipated.

Models were used extensively for testing materials and form during the design process. In his accounts, E6 emphasised the importance of physical models as a means of communication in the design process, regardless of the advances in computer technologies. Although E6 also considered computers to be an efficient means of visualisation, of communication between engineers, and of making for performing accurate calculations, he believed that physical modelling was superior in communicating three-dimensional qualities. E6 pointed out that, in the case of P6, physical models played an important role in convincing the client and the authorities. He then advised young designers embarking into the field of unconventional structures to employ physical modelling extensively as a design tool.

Finally, E6 identified two significant problems during the design process. The first problem was the preservation of the big ash tree in the middle of the site, and the second was minimising the structure as it was seen against the sky.

Summary.

The two interviewees gave very similar accounts of the design process of P6. They both, E6 in particular, described their working relationships with other members of the design team as good, although A6 reported having difficulties in his working relationship with LA P6. It was obvious from both accounts that there were very clearly-defined roles for each member of the design team. Both A6 and E6 expressed their enjoyment of the experience and the success of the project. As they pointed out, they later collaborated again to produce another similar structure.

Compared to the accounts given by A6, which were generally informative, E6 gave detailed accounts of the technical side of the design process. This was because the details were mainly designed by the engineers in collaboration with the contractor, while A6 concentrated on the overall design of P6. This also explains some of the minor discrepancies between their accounts. For example: although both A6 and E6 agreed that physical models were extensively and appropriately used as the main means of visualisation, communication and testing, A6 seemed unaware of the computer models built by the engineers for similar purposes and remarked that computers were only used for calculations.

There was also one contradiction between the two accounts regarding the solution for a minimum enclosure. While they both reported that LA'P6 was initially reluctant to accept the stainless steel mesh solution, which was eventually chosen over his cable net idea, they disagreed on the origin of the idea of the mesh solution. Both A6 and E6 claimed the idea as their own.

The structure was a success according to both A6 and E6, but for different reasons. For A6, it was a triumph to bring a perfect idea to reality despite strong resistance and scepticism. E6 cited the exploration of a new language of a new material as the most significant success of the design of P6.

P7

The diplomatic club in Riyadh, Saudi Arabia (1980).

Architects: AP7.

Consultant architects: AP7.

Structural engineers: EP7.



fig. 21. The Diplomatic Club in Riyadh, Source: Patterns 5 (1987), Buro Happold Office Literature, p. 20.

The diplomatic club is a matching of a rigid element, a wall, with stained glass tiled cable net and fabric structures attached to it (Ealey, Liddell and Pugh 1986). The strongest characteristic of all three of these elements is their three dimensionality. Although the resultant structure is elegant and original, it was difficult to handle design and erection because of this three dimensionality and the juxtapositions of rigid and flexible components.

History of P7.

The design team consisted of AP7, an architectural practice with local connections, A7P7, a consultant architect with vast experience in the field of unconventional structures, and EP7, an engineering firm with similar experience to that of A7P7 due to their previous collaborations. The expertise of both A7P7 and EP7 was necessary because AP7 did not have any previous experience in the design of unconventional structures. Hence, A7P7 and EP7 were involved very early in the design process to establish the feasibility of the structure and to help with form-finding.

The client's requirements were very simple. The brief specified spaces of different sizes for the building. The client had a limited budget for the project but time was not of major concern. The building took twelve months longer than expected to complete due to the contractor's inexperience in this field. During the design and construction period, the client kept in very close communication with the design team, paying frequent visits.

A7, 'principal in charge of the project' from AP7, was one of the two contributors that were interviewed. The second, E7, was an engineer from EP7 and a specialist in numerical analysis of engineering structures. E7 was in charge of the project on site. A lot of the design of P7 had to be done on site because of difficulties encountered during design developments. E7 was therefore in a position to provide a close insight into the progress of the project. His accounts were indeed very detailed with a great deal of technical information lightened occasionally by interesting anecdotes.

There are contradicting accounts regarding the authorship of the idea for the design of P7. The two versions of this story, both involving a young landscape architect working in AP7 at the time, were included in both interviewees' accounts.

Brief presentation of the interview with A7.

At the beginning of his account, A7 described himself as the head of the design team who 'thought of the design from A to Z including construction'. He strongly denied the story that it was the young landscape architect working in his office at the time who came up with the idea for P7. He insisted that the final idea was evolved by himself and the young landscape architect was responsible only for 'prettifying' one of A7's sketches. During a meeting between A7 and LA P7, the consultant architect, this idea was chosen in favour of previous suggestions.

A7 described the idea in relation to its response to the site which was beautiful but unfriendly. A7 compared the tents found in the beautiful areas created by the organic form of the wall to flowers protected between the curvatures of rocks. This idea, A7 added, also fulfilled the client's simple requirements for small spaces, which would be housed within the wall, and large spaces, which would be under the shelter of the tents. A7 recalled that he then further developed this idea in Riyadh.

A7 claimed that AP7 had previously carried out several tent designs which were never executed, and there were some other tents being designed in the office at the time. Therefore; according to A7, AP7 were aware of tent technologies. A7 believed that the idea was a simple one but, at the same time, realised the complexity involved in the design development and construction. Thus the involvement of LA P7 in P7, a leader in this field, was important. A7 regarded the input from LA P7 in bridging the gap between architects and engineers as paramount.

A7 described a love-hate relationship with LA P7. There were several disagreements between A7 and LA P7 regarding issues like the relative significance between the tent and the wall in the design and environment control inside the building. A7 described these disagreements as differences in opinion between himself and LA P7 as a result of having different attitudes and 'visions' - LA P7 was seen as innovative while A7 saw himself as more practical. A7 stressed his beliefs in his own 'rightness' regarding these disagreements. Although, according to A7, LA P7's ideas were ultimately very

practical, they were time-consuming ideas without any provisions to meet certain deadlines and fixed fees. As a result, these differences were mostly resolved in favour of A7. Nevertheless, A7 added that disagreements were healthy catalysts for the refinement of the design and it was a pleasure to collaborate with LA P7.

Meanwhile, the client, who had hand-picked the design team, had complete faith in their abilities and hence offered little interference during the design process. That increased the confidence of the design team.

In his accounts, A7 seemed to have lost enthusiasm during the detail design stage of P7 when technical issues begun to preoccupy the design team. A7, who was unable to recall the different stages of the design process, was also unclear as to who –the consultant architects or the engineers– actually initiated the design of details. He explained that the engineers was involved with the project right from the beginning. Although they were responsible for the design of details which was carried out during the design development, the details proposed by the engineers had to be approved by A7 with the support from the client. A7 also recalled that the choice of material was made collectively by the design team early on in the design process, and added that it was only through his persistence that the material was used at its full potential. A7 also described the choice of structure and materials from a philosophical view point.

Although A7 claimed that there were no major problems in the design process, he recalled that there were many difficulties on site. He explained that it took him another two to three years on site after the already lengthy design development stage to refine the design. He claimed that he was instrumental in making many necessary alterations. A7 was particularly proud of the fact that he won the dispute with the engineers regarding the fabrication of the ‘tent’, by making it out of one piece of fabric. It was, according to A7, the only single fabric tent of its size at the time.

Models were used extensively as a design tool and means of communication to A7, as well as sketches, working drawings and two presentation models. An incredible

number of working models were built during the design process and inventive modelling techniques were employed by A'P7. The use of computers was very limited during the design of P7 but A7 recognised that computer technologies could nowadays minimise the use of other means, and serve visualisation more efficiently than physical modelling even though there would always be some need for physical modelling.

He strongly believed in the interaction between architects and engineers from an early stage and was convinced that such an early meeting is necessary even if the building is conventional. Also he insisted that architects should develop a feel for the correct structural solution.

As a whole, A7 viewed P7 as a success in many aspects, which was very rewarding. The building performed efficiently and was much admired. He claimed that it would probably be built differently if he were to design it again but did not know how it would be different. In his opinion, the experience gained from this project, as from any other project, was valuable in his opinion. Also, he believed that P7 was the most beautiful work of LA'P7's career and that LA'P7 should be grateful that it was made possible by his, that is A7's, efforts.

Brief presentation of the interview with E7.

E7 recalled that P7 was more or less designed and was within a month of going on site when he was first involved. The contract had already been signed and the contractor was mobilising his team. The discrepancies between architects' and engineers' drawings in the design documents at the time was of major concern to E7. On top of this, E7 also recalled many 'internal difficulties' between AP7 and A'P7. As a result, P7 developed a poor reputation in-house. While the design team agreed at the conceptual stage of the design, differences of opinion became more apparent as the design team embarked on resolving details.

According to E7, the client imposed intense time pressure on the design team, because he wanted to demonstrate to the prospective occupants of P7 his commitment to the project. The design team were unable to resolve conflicts within the limited time allowed for the design period. Therefore, a full design team of twenty, including many architects and engineers from the original design team, was set up on site to co-ordinate and refine the design. At the end, it took thirty months, as opposed to the original estimate of eighteen months, to construct P7.

Further, once on site, E7 discovered that the contractors were not really qualified and did not have the necessary resources to realise the design. Even though the contractor had reasonably competent sub-contractors, the design had not been sufficiently resolved at that point to go to the subcontractors. However, according to the construction procedure in Saudi Arabia, the contractor had to take on some design responsibilities. This allowed the design team time to continue the design process during construction. This took place in the first one-and-a-half to two years while underground work, the construction of the wall and the installation of beams and cladding were been carried out.

E7 explained how he used his expertise in computer analysis and previous experience to good effect during construction. He felt that there was a lack of realism within the design team which prevented them from making the theoretical geometry real. E7 also felt that A7 did not fully understand the complexity of the geometry. As a result, the geometry proposed by A7 could not be realised. A7's proposal was realised from drawings only, which was, in E7's opinion, not accurate enough for this type of geometry. A great deal of calculation should have been carried out during the design development. Further, the contractors' lack of understanding of the design meant that they had to be convinced and reassured that the structure could be erected and that the geometry was correct. Therefore, A7 not only had to write the software in order to define the geometry and work out the three-dimensional intersections between the

complex curves, but also had to produce computer programs to realise the setting out with theodolites on site in three-dimensional models, for the contractors.

A'P7's involvement in P7 stopped after the concept stage. LA'P7 disagreed with the way the project was developed during the preparation of the construction documentation. E7 recalled in particular the conflict between A7 and LA'P7 regarding the relative height of the tents and the wall. E7 highlighted the importance of the involvement and contribution from A'P7 and EP7. Without their tremendous influence the building would not have been as successful.

E7 saw the disputes between three unequal partners of the international design team as one of the main problems of the design process. Also, this was one of the first projects of this scale and "international nature" in Saudi Arabia. He recalled that LA'P7 in particular had great difficulties tolerating the constraints placed upon the design team by people who, in LA'P7's opinion, did not understand the design. As a result, EP7 had to take on design management responsibilities and act as arbitrator mediating in many of these disputes.

The initial budget of R\$117,000,000 was increased to R\$170,000,000. This was sufficiently less than the contractor's tender. The contractors accepted the job at this price because they wanted to build up their reputation with this high-tech building so that they would be in a position to challenge for major projects in the future. The contractor was tied to a lump sum contract. E7 described how the contract document defined all the necessary materials but not necessarily at the right place. The engineers, in an effort to keep the cost of the project under control, played an important role in managing the cost and worked closely together with the contractor to adjust the design in order to balance the budget, so that P7 would at least achieve the same quality as in the original design.

E7 described the client as supportive. Although the client had seen the model and understood what was proposed externally, E7 explained that, apart from management

level input through the project manager, there was very little contribution in terms of detail work from the client's organisation, mainly because they did not have the knowledge to dictate the design of the structure. This allowed tremendous freedom for the design team on site, which was considered very encouraging in trying out new ideas. However, E7 maintained that the design team did not alter the brief but only the details.

Models were used extensively during the design process for visualisation and communication purposes, but not for testing. According to E7, the design team used a lot of full-scale mock-ups on site to test details. Although E7 was an expert in computing and stated that it would have been difficult to realise P7 without the use of computers, he stressed that computers were used only as auxiliary tools in the design of P7. Computer visualisation techniques were not available at that time.

Generally speaking, E7 strongly believed that design skill was independent of computing and that it was physically impossible to design only with computers. He insisted that, at a certain stage, designers need to design on paper where the hand provides the necessary link between the mind and paper. It is a mistake, in E7's opinion, to believe that engineers can dispense with architects with today's numerical visualisation techniques. E7 did not see design in terms of engineering only, neither did he believe that it should be seen only in terms of architecture. He viewed design as putting the two things together where physical modelling still had an important part to play.

E7 recalled the aesthetic and structural considerations regarding the choice of the construction and materials for the tents. This in turn had certain implications for the design of the environmental systems and the design of details. The design of details began in a very general way. Some of the components were standardised and some were modified from details used in previous projects by EP7. There were details

especially designed for this particular project. All the details were designed to give maximum flexibility to assist the erection process.

E7 explained that the appointment of the architect by the client was based on political grounds. The client wanted to engage a local practice in a major civil building. E7 shared LA P7's belief in the value of strong and correct ideas at the beginning of a design process so that the design process would flow smoothly. However, he disagreed with A7 and believed that it was the young landscape architect who had come up with the final idea in one of her sketches.

In general, E7 saw the building as a success, although he was able to point out a few technical defects. The high point of the building, according to E7, was its uncanny echo of the language used in traditional local architecture. He was, however, disappointed that the use of the building was changed after completion –from diplomatic club to a hotel. As a result, a number of the design aspects proved inadequate to accommodate the new use.

Reflecting on the experience with this project, E7 remarked that it is generally hard for an engineer who involves himself or herself in the design process of unconventional structures to go back to conventional design, which he described as less challenging.

Finally, E7 thought that the lesson to be learnt from the experience was one of team work. As he explained, the elements for an efficient team is the 'assemblage' of people who know one another's abilities and personalities.

Summary.

A7's accounts concentrated mainly on the concept and development of the design, while E7's accounts focused on the realisation of the design. This, as with several other case studies, was due to the different responsibilities in the design process of the interviewees. A7 worked mainly on the overall design in general and E7 made most of his contributions on site during construction. However, while E7 recalled a clear

picture of the whole design process, A7 was less clear on matters relating to the design of details and construction on site.

While both interviewees agreed that the members of the design team were hand-picked by the client, E7 provided more insight into the background of these appointments. E7 believed that political concerns played an important part at this stage, particularly the inclusion of AP7 in the design team.

The client had a lot of confidence in AP7 and therefore A7 was able to overshadow other members of the design team. A7, projecting himself as the dominant figure in the design team, credited himself with many decision-making responsibilities. His strong denial of the story that the idea for the building came from the young landscape architect working in his office at the time contrasts starkly with E7's version of the event, which accorded more credit to the young landscape architect concerned than A7 suggested. While A7, in his accounts, described the idea of the building in relation to inspiration offered by site conditions, E7 pointed out the idea in terms of its relationship with traditional local architecture.

Despite the lack of detail in his accounts of many technical issues, A7 claimed personal responsibilities for refining much of the design on site over a period of two to three years. E7, on the other hand, recalled thoroughly the site construction phase of the design. A7 was also very quick to point out his success in disputes over certain issues involving both LA'P7 and E7. His disagreements with LA'P7 on more fundamental issues of the design created a problematic working relationship between them. Nevertheless, A7 believed that both A'P7 and EP7 made valuable contributions to the project. This was also reflected in E7's accounts, when he suggested that P7 would not have been as successful without any one of the members of the design team.

Both A7 and E7 saw the building as a success as a whole. E7 regarded most of the failure of the building as the result of the change of use after completion. A7, on the other hand, did not mention, in his accounts, either any failure or the change of use.

P8

The Olympic Ice Stadium in Calgary, Canada (1981).

Architect: AP8.

Engineer: EP8.



fig. 22. The Olympic Ice Stadium in Calgary, Canada. Source: L' Industria Italiana del Cemento, N. 5, 1984, p. 312.

P8 is a building that can only be described in geometrical terms. Its purity derives from the interaction of three fundamental geometric forms: the sphere, the plane and the hyperbolic paraboloid; the result is a saddle-shaped “dome” (L' Industria Italiana del Cemento 1984). The architect's involvement and contribution in the design process of P8 was very limited due to the dominant structural considerations. The purity and simplicity of form facilitated construction and standardisation of elements, although it could be argued that this has taken away the potential architectural character of the building.

History of P8.

P8 is a large public building. Both AP8 and EP8 were involved in the design from the beginning. The building required a long span structure, the solution to which was a hyperbolic paraboloid concrete shell proposed by the engineer. The structure became the dominant element of the design which was visually expressed. This resulted in the engineer taking on a more dominant role in the design team, while the architects took on an unusually secondary role.

There was pressure for this public building to finish on time. This meant that the design had to be completed within a period of six months and the construction within two and a half years. This was achieved primarily due to the fact that the engineer had arrived at a solution at a very early stage in the design process.

A8, the principal architect of AP8, was interviewed, but his responses were relatively brief. This may have been a result of his limited involvement. On the other hand, E8, the principal engineer of EP8, gave a detailed account of EP8's involvement in the design process, with constant reference to the solution which was arrived at at the very beginning:

Brief presentation of the interview with A8.

A8 found it difficult so long after the completion of P8 to recall the details of the design, process in order to answer the questions in the interviews in a thorough and considered manner.

It was A8 who made the initial arrangements with the client who, according to A8, had strong ideas as to how he wanted the building to be. A8 explained that they were not unchangeable ideas. Only the function was an unchangeable issue which caused some restrictions for the design team. In fact, the brief was changed because of the peculiar function of the long-span structure. On top of that, A8 recalled that there was extra

pressure because the progress of the project was also monitored by the International Olympic Committee.

Although the client's ideas influenced the final decision considerably, they were not followed entirely, because of economic considerations. The building, according to A8, eventually cost C\$16,000,000 more than the original budget. A8 reported that the client did not have any major concerns during the design process.

Time was of particular concern for the design team. Although there were no delays in the original schedule, the design process had to continue even when the building was being constructed, due to the numerous changes involved. A8 recalled that the construction period of the building took thirty months.

According to A8, there were three structural types proposed at the beginning: employing steel, fabric and concrete. The condition of the urban site, and wind and snow loading considerations were taken into account for the final decision in which concrete was chosen. A8 recalled that this happened at the beginning of the design process.

A8's perception of the working relationship amongst members of the design team differed from that of E8. A8 realised that some members of the design team had previously worked together, but did not recognise any members as dominating. There were no major disagreements, but that was perhaps because the group was not interacting. Architects and engineers were working separately and made decisions in their own field.

A8 did not recognise any design idioms or influence from traditional local architecture in the design of P8. Neither did he see the design of P8 as an exploration of any new languages. He was not aware of any technical references used during the design process. A8 recalled that both physical modelling as well as hand drawings were used as means of communication and exploration. Mathematical calculations, though not by

computer, were thought necessary for the form finding. As well as employing standardised components, the design team designed the majority of the details. A8 could not pin-point the most significant problem of the design process.

Due to the unconventional nature of the structure, AP8 was totally dependent upon the input given by EP8. Although he believed that it could be designed differently today, A8 thought that P8 was a successful building and offered itself as an example of this type of structure. Based on his experience, A8 stated that a young designer 'has to research, analyse and test alternatives putting particular emphasis on buildability'.

Brief presentation of the interview with E8.

In the beginning of his interview, E8 maintained that the architects did not dictate anything during the design process. He also pointed out that it was the engineers who arrived at the concept. Originally, there were three structural solutions proposed. E8 explained that cost and structural efficiency considerations were the deciding factors for the choice to use concrete. E8 also mentioned how they were surprised that it was the cheapest solution out of the three.

E8 remembered meeting the client and the architects almost simultaneously, at the beginning of the design process. He recalled that the engineers were immediately given a free hand with the shape of the building in finding a structural solution. The architects were responsible for the architectural finishes to 'prettify' the structure. According to E8, the principle of the design had always been to express the engineering of the structure.

E8 explained that, due to the fast-track nature of the project, there were no special phases in the design process. The design was carried out on the basis of solving the problems as and when they arose, due to extremely tight time schedules imposed by the International Olympic Committee.

The harmonious communication between architects and engineers was seen by E8 as extremely important in order to ensure a smooth design process even though there was very little communication between the architects and the engineers after the initial design stages. E8 also attributed the success of the design process to the engineers' dominant role in the design team. He believed this dominance was justified because of the unconventional nature of the project.

Several times during his interview, E8 emphasised the importance of arriving at a simple and correct idea right from the beginning of the project. He explained that the idea for E8 remained the same all the way through the design process, because the idea was correct in principle. As a result, there were, according to E8, no significant problems or unforeseen difficulties in the design process. E8 also pointed to this as advice to young designers involved in unconventional structures.

E8 recalled the use of physical modelling for understanding the geometry and for establishing wind loads, which was the predominant factor affecting the design. Computers were used much later on for the design of details. E8 also mentioned physical models made for presentation purposes. E8 was sceptical of the reliance on computer technologies, especially without fully understanding the task involved, because of potential catastrophic consequences if anything went wrong. E8 also believed that computers could never be used to develop conceptual design.

E8 maintained that the engineers were responsible for designing the details, even though there were specialists involved in the design process. The details were always proposed by the engineers from scratch or by modifying specialists' details.

The design team kept in touch with the client through weekly meetings. Even though the client did not engage in discussions of architectural issues, he made many decisions with the advice from the engineers. However, E8 did not see the client's involvement as a hindrance, but as a positive aspect, as it streamlined the design process.

E8 identified the three-dimensional nature as a distinctive feature of unconventional structures which can make visualisation more complicated and difficult. E8 believed that the experience of the architect played an important part in his understanding of engineering issues. In his opinion, lack of that experience could cause problems of communication between architects and engineers. He further identified what he called 'the difference between the engineering question and the architectural question'. As he explained, while inexperienced engineers would never be put in charge of a project in an engineers' firm, many young designers in architectural practices are allowed to oversee the concept design of a project, which often results in unbuildable designs.

The cost of the project was overrun at the end. According to E8, this was justified and was mainly due to changes (e.g. into a multipurpose hall) and additions imposed by the client during the design process. The design development stage lasted for six months before construction began. E8 recalled that there was only three months to make all the necessary decisions. The construction lasted thirty months, twelve of which were taken up with the erection of the structure.

According to E8, the building was a success and he would not design it any differently today. E8 explained how the structure worked very efficiently with very low maintenance costs. However, he expressed a slight disappointment over the outcome of the architects' intervention regarding the colours selected for the building.

Summary.

A8's accounts were extremely brief compared to those of E8. This was mainly because the project was dominated by engineering considerations. Further, there was a very distinct allocation of tasks between the architects and the engineers. The architects and the engineers made their decisions separately, with the client's consent. The architects, therefore, seemed to be unaware of many of the engineering issues. A8 admitted that he was totally dependent upon the engineers. E8 attributed the success of the project to the

early decision on the correct solution by EP8. In general, however, the two interviewees' accounts of the design process were fairly consistent.

There was very little interaction between the architects and engineers. On top of that, unlike many other case studies, there were no consultant engineers or architects involved, apart from the proof engineers. As a result, there was complete harmony between the members of the design team. E8, meanwhile, was proud of the achievement of EP8's involvement in P8.

A8 did not see this project as an exploration of a new language. In general, it appears from A8's accounts that he did not consider the unconventional nature of the structure of P8 as an important issue.

Both A8 and E8 thought that P8 was a success although E8, in his accounts, commented on several minor disappointments over the architectural treatment of the building. E8 cited the limited budget for architectural works and increased spatial requirements from the client towards the end of the construction period as the main causes of these imperfections.

P9

The Schlumberger Research Centre in Cambridge, U. K. (1985).

Architects: AP9.

Structural engineers: EP9.

Membrane and cable engineers: E P9.

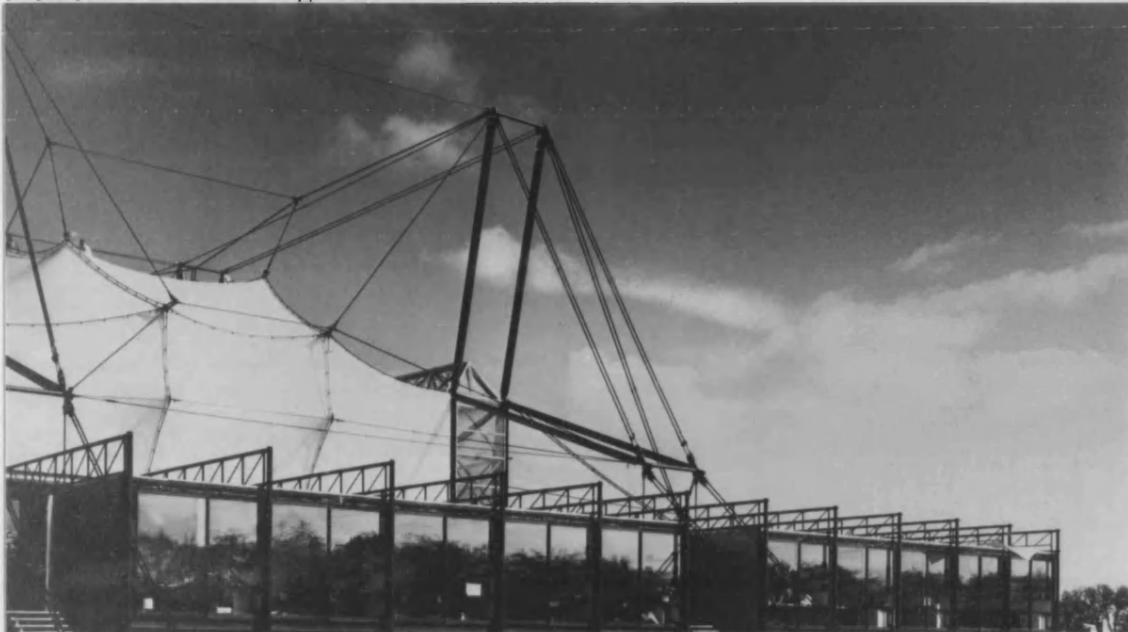


fig. 23. The Schlumberger Research Centre in Cambridge, U. K. (1985).

Although the form of the building was originally thought to be conventional, its purpose dictated an open, column-free and high-headroom space. The office units formulate an in-between space that facilitates the reception at the office level, and part of its area is on a lower level that accommodates the laboratories. The whole system is covered with PVC fibre membrane that is stretched by an external structural system of repetitive prismatic girder bays and masts (Haward 1984). The design process, apart from the innovative form, had to deal with the different environmental conditions that laboratory space and office area under the same roof demanded. The building has won good critiques that justify the choice of the structural type and its particular feature of flexibility to expansion. However, the “new expansion” has nothing in common with the original building. It is a detached building of a different, conventional structural type.

History of P9.

P9 was designed by AP9, with EP9 as structural engineers. E'P9 joined the design team as engineers to work on the unconventional structure involved in P9. This was the first time that AP9 had worked with E'P9. However, both of them had previously collaborated with EP9, who therefore provided the common link. The working relationship amongst these parties was reported to be very good.

Brief presentation of the interview with A9.

A9 recalled that the brief was developed over a long period of time by establishing the requirements from the future occupants. An ideal diagram for the design was then developed. This consisted of quiet cellular office spaces next to a very large test space. The original design of P9 did not include any membrane structures. It was not until half way through the design that a membrane structure covering the central part of the building was considered as an appropriate solution. This idea was first introduced to A9 by an engineer with whom he was working on another project at the same time. An additional set of engineers was required because of the special expertise involved in the design of membrane structures, which, according to A9, were very uncommon at the time.

E'P9 was introduced into the design team by a contractor who was involved as a consultant. Although this contractor was not chosen to execute P9, E'P9 remained in the design team. There were other consultant engineers involved apart from EP9 and E'P9, for example, the engineers from the main contractor, engineers from the acoustic consultant, etc.. Apart from EP9 and the acoustic consultant, A9 had not previously worked with the others.

A9, who was responsible for arranging the appointments of consultants with inputs from the client, was relieved that there was a good working relationship amongst the members of the design team, despite the complicated arrangements, especially as E'P9

was brought in half way through the design. He attributed this good relationship to the successful combination of individuals.

A9 described the client as very understanding, with active participation. He understood the job well and worked well with the design team on the decision making. A9 did not see that as a restrictive interference but as a benefit to the design process. The client's involvement from the beginning enabled him to follow the logical evolution of the process, which led the design team towards employing an unconventional structure in order to meet the objectives of the brief.

A9 did not regard the difficulties occurring during the design process as 'fundamental' disagreements. These difficulties, involving, for example, the environmental system, were seen by A9 as part of the design development which helped to keep the design team working hard. According to A9, all the members of the design team agreed on the solutions to these difficulties at the end.

A9 claimed that the design process was a joint effort but, at the same time, stated that there was more effort from the architects. Nevertheless, A9 recognised the contribution from the other members of the design team. He claimed that the project could not have been done without any one of them.

A9 described the decision to employ the membrane structure solution as based on functional considerations. He did not see it as a decision to "go unconventional" at the time, because it was very logical. In general, A9 did not consider the design of unconventional structures as different than that of conventional structures. A9 believed that the design of both types of structures require the same amount of thought process. Throughout his account, A9 never specifically distinguished between the conventional and the unconventional aspects of P9. For example, he did not emphasise the unconventional roof structure when discussing issues related to the benefits of knowledge gained from previous experience. The reason why there was no distinction between conventional and unconventional structures could probably lie in the fact that

most of the projects AP9 design are unconventional, according to the definition of unconventional structures used in this thesis.

The design of details started relatively late during the design process, when the sub-contractor joined the design team. While the details of the conventional part of P9 comprised mostly standardised components, details of the membrane structure were designed by E'P9 and refined by the sub-contractor with approvals from AP9. A9 felt that the contractors' input was vital to the design of details. Also, according to A9, the material for the membrane was chosen surprisingly late. A9 maintained that the material chosen was the best, although it required more frequent cleaning than anticipated.

Although A9 claimed that there were no unforeseen problems with the erection process, he underlined the different techniques involved in the erection of an unconventional structure. These techniques were mainly required to tune-up the structure because it was all a 'live structure' and everything needed tensioning down and the lengths had to be absolutely right. It took considerable time to ensure that correct adjustments were made and everything was positioned accurately.

A9 regarded learning from previous experiences as a self-educating process. He stressed that everything learnt from previous experiences should go towards assisting the next project, but pointed out the danger of adopting "short-hand" solutions without careful consideration. Also, A9 did not believe in any conventional wisdom of the design process. He added that each architect develops his/her own culture from his/her education and background, learning and borrowing from examples.

Physical models were used for visualisation purposes from the beginning of the design process and computer models were also used later. These two types of models, together with hand-drawings, were used to communicate ideas to the client and amongst the design team. Nevertheless, A9 had a very clear idea about the role of computers and physical models in the design process in general. He argued that computers are necessary for the co-ordination of the building, and to provide precise

drawings, whereas physical models are necessary for better perceptions of the building. A9 saw computers only as a design tool to be used in the later stages in the design process for the realisation of initial ideas.

The most significant problems of the design process were the tight time schedule and budget constraints imposed by the fast-track contract. Nevertheless, A9 also saw the danger of overdesigning if there was more time for the designers. A9 reported that there was a slight cost overrun, while the design took twenty months, which continued into the fifteenth to sixteenth months of construction.

A9 believed that P9 was a success, even though there were some inevitable minor technical defects. Although he claimed that it would probably be designed differently today, he had no regrets about the result. P9 was particularly significant to AP9 as it was designed and constructed at a very vital stage in the development of the office. AP9 learnt a great deal from P9 on aspects of innovation, importance of expertise, confidence and assembling of a design team. Also, the experience showed A9 the limitations of the building industry and its abilities to deliver unconventional structures. Finally, A9 pointed out the lesson that, for innovation to be achieved, a lot of determination is necessary.

Brief presentation of the interview with E'9.

According to E'9, E'P9 was approached by both AP9 and the client of P9 to carry out the design in conjunction with EP9, who was carrying out the design of the steel structure. E'9 was reluctant to comment on whether this arrangement was related to the abilities of EP9 in the field of unconventional structures. As E'9 recalled, the design team enjoyed a particularly good working relationship because some of them had worked together previously. There was good communication amongst the members. In general, E'9 stated that the most important element of the good relationship between architects and engineers lay in the will of the latter to 'listen' to the former and 'draw things in 3D in front of the architect'.

The 'debates' (according to E'9, there were no disagreements) were seen by E'9 as positive elements of the design process which, in that instance, acted as a stimulus for EP9 to become more inventive. The main debate was associated with the extent of the membrane. This was resolved in E'P9's favour and the membrane extended to enclose the end walls as well as the roof of the central part of the building.

The means of communication amongst architects, engineers and the client included basic hand drawings and sketches, physical models and elaborate computer modelling. E'9 pointed out that the computer visualisation techniques used by E'P9 were advanced compared to those being used in other engineers' offices. E'9 explained that the use of computers was particularly useful in this project because of the client's familiarity with this field.

In his accounts, E'9 further discussed the issue of communication between different disciplines in the design team and its association with education. Generally speaking, architects are trained to understand concepts; engineers tend to be more trained to use rules; and public officials like to have a book of regulations. As a result, architects are generally quick to handle concepts and can understand them more readily than some engineers. E'9 also stressed that architectural education should develop a greater 3D sense than engineering education does. E'9 noted that the different complicated languages used by architects and engineers ("architect speak" and "engineer speak") caused a great deal of confusion. He encouraged the use of simple language to describe physical phenomena.

E'9 recalled the architects' reluctance to develop technical solutions but, on the other hand, valued the vast contribution the contractor made during the design stage. Although E'9 believed that the contractor is generally being considered as another member of the design team nowadays, E'9 stressed that this will not undermine the consultant engineers' intellectually dominant position within the design team. He went

on to suggest that, because of the diverse interest in different fields of structural design, engineers generally tend not to specialise only in lightweight structures.

Although E'9 claimed that cost and time considerations was not his concern (but that of the architect), the time constraint was seen by E'9 as the most significant problem of the design process. He related this to the design team's relative lack of experience in this field. He also recalled, contrary to A9's account, that there was no cost overrun, but a time delay.

On the whole, E'9 thought the building was successful architecturally, structurally and environmentally. Nevertheless, he added that it would obviously be designed differently today because of the experience gained since. Finally, he strongly emphasised and admired the architects' courageous insistence on using a single-skin membrane, regardless of the implication of heat transfer between the inside and the outside of the building.

Referring to the idea of using unconventional structures in an innovative manner, E'9 pointed out that, not only is a specific environment necessary for inventive design, but also enthusiasm is required from all the parties involved.

Summary.

In general, the two interviewees' accounts were very consistent. They gave very similar accounts of the development of the design. They both regretted that there was such a strict time constraint, but A9 also recognised the benefits of having to make decisions in a short period of time.

Unlike other case studies, the unconventional aspect constituted only part of the structure of P9. As A9 explained in his accounts, the design team arrived logically at the solution of the membrane structure half way through the design process. After some complications, E'P9 was appointed to carry out the design of the membrane structure in conjunction with EP9 who would carry out the design of the steel structure. As a result,

A9's reference to P9 often concerned the overall design, while E'9 referred mainly to the membrane structure.

Both interviewees enjoyed the good communication and working relationships between the members of the design team. The design process was very smooth without major disagreements –only according to A9 were there difficulties , while E'9 spoke of debates only. They also valued the contribution of the contractors in the design of details. Although E'9 recognised the increasing importance of the contractors' role in the design team, he believed it was unlikely that they would ever become dominant members.

The building was a success according to both A9 and E'9. A9 described the experience gained from this ambitious project as very valuable, since it coincided with a vital stage in the development of AP9. E'9, on the other hand, did not consider the design of P9 as an innovative experience, because E'P9 had already built several similar structures.

5.4. Brief presentation of interviews with A and E.

The following section is a presentation of the interviews with A and E who are pioneering designers in the field of unconventional structures and have participated in most, but not all, of the case studies.

5.4.1. Brief presentation of interview with A.

At the beginning of the interview, A emphasised that the design team is a very important aspect of the project. He stressed that a good design team depended upon good control as well as the individual characters. Speaking from experience, he would firstly form the design team by hand-picking people with known qualities and then almost immediately allocate tasks according to these qualities.

Having established the team, it is important for the team to be confident. Although A believed that confidence can be gained through experience, he was quick to point out that every case is different and that some obviously would be more difficult than others. He did not believe that there are any rules young architects inexperienced in the field of unconventional structures can follow. Knowledge, confidence and trust are the main ingredients for success.

A saw himself as operating in a different way from normal architects. He carried out experiments in what he called 'physics studies', without any specific functions. Very often projects began when clients saw in this experience a possible solution to their problems. A referred to these types of experiments as 'studies in the basic laws of structures'.

He specifically differentiated basic from applied research. Much basic research had already been carried out decades ago. The results of this research were well understood and they did not need to be repeated again. However, applied research had to be carried out once basic decisions concerning a project had been made. Although some basic research might also be necessary at this stage, it still tends to be dedicated to a certain

application. Very little basic research has been carried out by contemporary architects in the same way as carried out by A. A believed that this research could not be taught even at university level. The nature of these studies meant that it was not possible for anyone to say things should be done one way or the other. For this very reason, A did not see himself as a teacher.

The only advice A would offer young designers was to work in a team together with experienced designers to see how things are done, as this being the only way to step into this 'craftsmanship between research and design'. The most important thing is to learn by listening and observing, especially at the beginning, when the main decisions are made.

On the subject of working relationships between architects and engineers in unconventional structures, A strongly believed that engineers should join the design team from the very beginning, at the same time as the architects. These two disciplines of the design team should work very closely from then on. The normal practice, where the engineers were involved at a much later stage when the preliminary design (or even scheme design) had already been produced, cannot be applied to unconventional structures. In many cases, the role of the engineers might become equal to, if not more important than, the architect's in the design of unconventional structures. Depending on the quality of the engineer, he or she might even become the dominant member of the design team. Although this is the norm for many engineering structures, like bridges, towers, earth buildings, etc. this is not true with architectural structures in general. Unconventional structures fall between these two, there being are no rules as to which role is more important.

Reflecting on his past projects, A thought that every building would be realised differently today. Even immediately after completion of the building. There could always see ways which they could be improved upon. Since these buildings were of new forms and used new technologies, inevitably they all had weaknesses. Also, the

differences meant the techniques used in one project could not simply be applied to the next.

Here, A made perhaps the most important point of this interview, which was to a very large extent was reflected in the interview with E. A highlighted the importance of correct decisions being taken from the very beginning in order to ensure a smooth design process. In his opinion, these early decisions, which should include ideas about materials, details and adaptation to the landscape, etc., should be 80% correct. The remaining 20% could be achieved by adaptation later on in the design process. If these decisions were made incorrectly, changes and compromise to be made in the later stages could result in an inferior building. For example, if decisions were made according to the architects' vision, incorporating 'a wrong structure for the wrong function', it would inevitably lead to major problems later on.

A again emphasised that the engineer had to be involved at an early stage, although he or she might have to wait before they could begin carrying out the task of determining and calculating the structure. Only 'brains' (imagination) are required at this stage for ideas, not calculators or slide rules for calculations. The engineer should be able to state whether the vision ('the building in the air') is buildable, without resorting to calculations, even down to considerations of details if necessary. There would simply not be enough time and money for calculations. A further stressed that every member, not only the engineers and the architects, but members such as landscape architects, should also be involved, especially with large buildings.

On the subject of communication techniques with other members of the design team (more specifically the client), again A believed that the unique nature of every project made it impossible to make any rules. Neither did he express any preferences for using physical or computer models. Hand drawings, physical and computer models should, in A's opinion, always be used in parallel. He further distinguished presentation models from working models. The former are more time-consuming and expensive, the

latter can be constructed very quickly and cheaply and are more useful during the development of the design in general.

Finally, A believed that there were opportunities for further exploration into new technologies and inventions, new forms and new materials (even unmaterialistic force transmission). In his opinion, structural evolution is also possible despite its slow development.

5.4.2. Brief presentation of interview with E.

E began the interview by reflecting on some observations he had made on the beginnings of the Sydney Opera House project, which he went on to discuss at great length with very interesting insights. He recalled the unusual judging procedure as well as how the winning scheme influenced a project one member of the jury was carrying out at the time. It was through another member of the jury that the architect of the winning scheme was introduced to EP, which was a small firm at the time. On the winning scheme, itself he recalled that it was designed without engineers' input and that it was physically wider than the site. Although the concept was brilliant, the architect's model did not work structurally.

Although a local contact engineering firm was established and one of the engineers from this firm subsequently joined EP, there was very little exchange of information at the beginning. Nevertheless, the engineers set up two different groups. One group was responsible for the substructure and the other for the roof shell. Based on the limited amount of information, crudely worked out assumptions were made. This meant that the design team was struggling for a long time and getting into more and more difficulties.

With the benefit of hindsight, it was clear to E that the best thing to do at that time was to take an entirely new look at the design to see if any radical changes could be made. This was never done, because the engineers were afraid of the extra time and effort this

would involve. However, E argued that, in reality, the amount of work and time involved in redesigning would be minimal, because there was already a great deal of knowledge of the project. Instead, the team decided to begin construction of the substructure without having solved the roof shell problem. This proved to be a very costly decision.

Unlike today, when simultaneous design and build seems to be the norm for large projects, management techniques at the time had not been developed sufficiently to cope with overlapping design and construction in an organised manner. Three years after construction of the Sydney Opera House began, emergency crisis meetings had to be held in order to find a solution once and for all.

One of the changes made at this point was that the engineer-in-charge of the project in EP was replaced by another engineer who, though in his opinion was not necessarily a better or a worse engineer, took a harder and more ruthless line towards the architect. This, according to E, contributed to the resignation of the architect. However, it was ironically the architect who eventually came up with a solution before he resigned.

With hindsight, E believed that the architect was perhaps the only person capable of finding a solution, because he was the only person who would agree where the rules could be bent to allow a suitable solution and who would have refused to accept any compromises. E also identified the first engineer as one who could 'look into the wood'. He believed that this type of engineer would inevitably be underrated. They tend to have a low profile and make the people around them work by allowing them the glory. However, the atmosphere in which the team of engineers was operating was so stressful that one of the partners destroyed the career of a fellow engineer after firing him from the practice.

E also suggested that the conflict caused by the personality of the architect contributed, to a certain extent, to the difficulties encountered during the design process of the Sydney Opera House. He, nevertheless, saw that conflicts could sometimes be

constructive. He strongly believed in the architect's genius, which was only flawed by his failure to collaborate with good quality engineers.

E thought that the Sydney Opera House was in a way a failure, because it did not contain the spirit which the architect saw in his imagination. Nevertheless, the building now symbolises Australia in the same way that the Eiffel Tower symbolises France. At the end, it was EP1 who received the recognition for the building but not the architect – a fact E thought the architect resented.

In conclusion, E believed that a lot of what happened in this project, and to a large extent in other large projects, such as the Pompidou Centre, the Mannheim Garden Centre and the Munich Aviary, were very often governed by political issues way outside any artistic concerns.

E then raised the subject of working within another culture. He believed that working in an environment away from one's own system would often offer better chances for innovation. E even noticed a difference between those working in Stuttgart and Munich doing the project for the Munich Olympics.

This led to a discussion regarding the exchange of information. E thought that one of the best ways of checking design was the exchange of drawings. He also observed that many architects like to live with uncertainties and want engineers to make decisions for them. This in his opinion, was not a good way to design, as it shortcuts a great deal of the 'exchange of information' and hence opportunities to identify mistakes.

E saw his work as selling dreams to clients and believed that his practice has produced many good buildings, even though it might not have been justly rewarded financially. He also thought that his practice's reputation for being strong minded has made it difficult for architects in this country to work with him. This to some extent explains why most of the work his company was involved in comes from abroad, where there are more innovative situations.

E believed it was the risks involved in innovation that drove them forward. The higher the risk, the more efficient one becomes. The less one wants to take these risks, the less confident one becomes. He also distinguished architects from engineers by stating that not only was there a larger grouping under the title 'engineers' but also that engineers' work very often incorporates a management role.

He insisted on using the practice's past experiences to good effect. Not only would he be able to avoid making the same mistakes, he would not give up pursuing good ideas even after the completion of a building. He would try to explore the possibilities further. He recognised the enormous amount of research been carried out in this country which is not necessarily industry-based. He also noticed the change in the attitude towards research in Germany, which generated a lot of research that architects believe ought to be done.

Finally, he believed that one of the problems with lightweight structures is the inability of the present system to justly reward the designers financially for a successful structure which incorporates a minimum amount of material. The cost of these structures would in theory be less than that of a conventional one, hence reducing the fees for the architects and engineers proportionally.

5.5. Explication of story line - Paradigm Model.

After the open, axial and selective coding stage, further and intensive reading of the coded interviews occurred so as to select and refine the core category. The present study was intended to explore differences between the design processes of conventional and unconventional structures and extra difficulties that may appear during the design of unconventional structures. The focal points were found to be:

- i. the qualitative identification of the differences and difficulties, and
- ii. the proposition of ways in which these differences and difficulties could be understood and handled.

More specifically, the aim was to provide awareness for designers and the objectives were to address how various types of awareness (context) come to be conditions for action and reaction, how they are maintained (strategies) how they change (process) and what that means for those involved (consequences).

The data indicated the association of unconventional schemes with innovation that they initiate. That in turn was linked to the several unknown factors which make the design process distinctive and problematic, as well as challenging, to most of the respondents. The degree of the distinctive and problematic nature of unconventional structures varied in the designers' perception. In most cases, the design process was described as a complex, risk-taking action. The design teams of the present study were chosen to a greater or lesser extent to push the projects forward, so that they would become real buildings.

Following the selection of the core category, its refinement and further understanding occurred. The study of each individual case attempted to identify patterns of:

- i. The ways in which risk-taking or difficulties differ for each of these contexts,

- ii. the options which the designers were balancing in each context and the way in which their desire for a good building influenced the decisions that they made, and
- iii. the form that joint management took in each context, in terms of controlling strategies.

An abstract model, the Paradigm Model, which explains the linkage and association of these issues, emerged after the axial coding of each case. The axial coding mini frameworks describe the linkage of context-strategies-process-consequences.

More specifically, the core category was identified as being the association of an unconventional proposal with the process that has to be followed in order that it be executed. The properties of an unconventional proposal were related to its innovative nature, which was in many cases the outcome of a flexible brief. The only difference from the requirement of conventional proposals is to cover a long span, to produce a column-free space. However, this only changes the nature (specific dimensions) of the design process which becomes in certain respects different from and more difficult than the design process of conventional proposals. The main points of differentiation and difficulty lie in:

- i. the interrelation and interdependence of architectural and engineering considerations,
- ii. the outstanding importance of environmental, planning and urban considerations,
- iii. the determining role of the choice of material to the form and structure and vice versa, and
- iv. the significance of the design of construction details.

The fulfilment of the requirement for roofing a long-span column-free space lead to a solution dominated by engineering considerations. As a result, the organisation of the design team is also affected. The allocation of tasks and attribution of responsibilities becomes unclear. The exchange of information between architects and engineers

becomes more difficult. Participants misunderstand the aim, nature and chronology of using different means of communication.

On top of that, problems (intervening conditions) such as time and cost limitations, lack of specifications and restricted use of standardised components, difficulties of convincing authorities and lack of precedent buildings appear to exist.

Respondents attempted to suggest possible ways (strategies) in which the problems could be reduced. These involved issues of allocation and timing of participation of different disciplines, the close relationship between form and structure, the design of details and choice of materials, the exchange of information and conveyance of knowledge among young and experienced designers, the organisation of the group, and the frame of mind in which the designer must be before attempting innovation. Detailed discussion of all these issues follow in the next chapter.

Causal Condition
unconventional building

Phenomenon
differences and difficulties in the design process

Properties of Unconventional Building

1. Innovative outcome of a flexible brief
- 1.1. Fully flexible
- 1.2. Cover long span, column free space
- 1.3. One restriction only
 - 1.3.1. Ecological
 - 1.3.2. Economical
 - 1.3.3. Satisfying the user

Specific Dimensions of Design Process

1. Different and difficult design process
 - 1.1. Architectural and Engineering considerations
 - 1.2. Environmental, planning and urban considerations
 - 1.3. Choice of material
 - 1.4. Constructibility and design of details

unknown technical issues —

individuals with different degree of
experience
education
'special understanding'

2. Organisation of the team building

2.1. Team roles

2.1. Individuals' exchange of information

2.3. Means of communication

aim

- communication
- simulation
- visualisation

chronology

- at commencement
- midway
- towards the final stage

nature of means

- physical modelling
 - computers
 - hand-drawings
 - hand-calculations
 - three-dimensional geometry
 - discussions
- conceptual detailing
- wind-tunnel testing
- presentation to client

3.1. Group

3.1.1. Group environment

3.1.2. Group size

3.1.3. Group norms

- group think
- determination
- motivation
- enthusiasm
- fame, glory
- trust
- personal closeness
- respect
- remuneration

- innovation
- risk taking
- power
- antagonism
- conflict
- competitiveness
- interpersonal relationship

- individualism
- bias
- uncertainty
- anxiety
- favouritism
- conflict of interest
- aggression
- personality clash

- fixed small groups
- flexible to increase

position in the group

contribution to the group work

1.1.1. Leader

- consulting
- consulting and managing
- leading decision-making, organising team

- non-chairman
- extrovert innovator
- authoritarian

1.1.2. Architect

- winner of competition
- consultant
- assistant
- adding late architectural 'input'

- core worker
- part-timer, consultant

1.1.3. Engineer

- technical, 'structural'
- 'architectural'
- key-calculator, 'back-room' engineer

- core worker
- part-timer, consultant

1.1.4. Client

- active participant in decision making
- passive participant

- passive
- active

1.1.5. Contractor

- consultant
- sub-contractor

- part-timer
- core worker
- consultant

1.1.6. Proof engineer

- qualifier

- consultant

Strategies for Design Process-Team Management

- simultaneous and equal involvement of architects and engineers
- more time spent on decision-making and design of details
- form seen as a result of the analysis of forces
- importance of detailing
- early choice of material
- collaboration with pioneers when young
- group division into sub-groups after decision-making
- understanding of scale of unconventional projects, commitment and determination

Intervening Conditions

- time and cost limitations
- lack of specifications and restricted use of standardised components
- difficulties in convincing authorities
- lack of precedents, and standards

fig. 24. Paradigm Model

Chapter 6. Research Procedure, Analysis and Presentation of Findings, Phase II.

6.1. Introduction.

This chapter firstly analyses general issues that appeared in the Paradigm Model (see previous chapter) by interrelating and cross referencing them in order to draw various conclusions regarding the research questions addressed at the beginning of the thesis. Secondly, the intentions of the questions of the interview guide are discussed, following the same process of interrelation and cross reference. Lastly, the completion of the story line is attempted, so that conclusions can be drawn.

6.2. Description and analysis of issues raised in the Paradigm Model.

The causal conditions and phenomena have been discussed in the previous chapter. This chapter will discuss the properties of the unconventional scheme, the specific dimensions of the design process and team, the strategies for design process and team management and the intervening conditions. The numbering system of the sections below refers to the numbers on the Paradigm Model. This should not be confused with the numbering system of the sections of the thesis.

As was explained in chapter 4, according to the Grounded Theory approach, further and intensive reading of the coded interviews occurs after the selective coding stage, so that the core category is selected and refined. In the present study, the repeated presence of the characteristics of unconventional structures and reported difficulties that may appear during the design process needed to be monitored. The focal points were found to be:

- i. the identification, qualitatively, of the difficulties, and
- ii. the proposition of ways in which these difficulties could be handled.

6.2.1. Properties of unconventional scheme.

i. Participants associated the degree of innovation with the flexibility of the brief. Three not very dissimilar types of briefs were identified; firstly, the 'non brief', secondly, the brief with one general requirement, and lastly the brief with one or more restrictions. When there was no brief, the design team had the freedom to propose 'exciting and fancy' schemes. For instance, in P4, this freedom allowed the design team to reassess the initial idea and suggest an entirely new one which was finally executed. The interviewees of the project recalled the excitement generated by the chance they had to experiment on a 'new structural type'.

ii. In the second type of brief, the ultimate requirement of the brief was, for instance, the coverage of a long-span column-free space. In many cases, the functional need to cover a long-span with minimum material led to an innovative solution, while innovation was not an objective of the brief or a conscious intention of the design team.

iii. The third type of brief gave freedom while establishing one or more objectives which had to be met. Sometimes, the main concern of the brief was for the building to be sympathetic to the users, economical, ecologically acceptable and adapted to the landscape. In P6, for instance, part of the brief concerned the issue of saving the landscape by minimising the structure. In some cases when architectural considerations, such as adaptation or function, and engineering considerations, such as economy or minimisation of the structure, had to be taken into account, the brief was finalised by all participants, -architects, engineers and client. In other cases, when function and the requirement of coverage of a long-span were the sole objectives of the brief, the architectural input was limited and hence the resultant building was architecturally uninteresting.

Overall, interviewees appeared to consider freedom of the brief necessary for innovation to occur. In many cases, flexibility of the brief was considered an advantage for the design team. Participants argued that an unconventional, three-dimensional form

requires a flexible brief where changes can easily happen. That was implied in E8's comment: 'with innovation there is no way to know how far it can go' .

However, some participants argued that the flexibility of the brief can generate confusion regarding the role clarity of architects, engineers and the client: 'there was no really committed hard edge between the architect, engineer and client to which way to go' (E1).

6.2.2. Specific Dimensions of design process and team.

Difficult and different design process.

1.1. Architectural and engineering considerations.

The findings indicated that architectural and engineering aspects of the design process of the case studies were strongly related. The findings also showed that the form must be dictated by the analysis of forces in the structure. Therefore it is appropriate to discuss them in parallel within the same section.

In their accounts, participants explained that the nature of any unconventional scheme is 'ambiguous' (A). As a result, these structures are 'hybrids of architecture and engineering' (E6). The difficulties of the design team in understanding the qualities of such a scheme were attributed to this ambiguity. This imbalance between aesthetics and function was the problem in P3. According to A3, 'aesthetics was the dominant issue which wrongly replaced function and structural considerations of the design team' .

In some cases, lack of precedents and conventions of architectural norms constituted another problem. Designers talked about a 'new architectural vocabulary' (E6) and the necessity of 'different to normal architectural devices' (A5). For instance, A5 talked about 'the organic forms of windows, the softness of the cladding and the absence of framing'.

Participants very often commented on the difficulties of the unconventional 'sky-to-ground progression' (E5), the 'adjustment of a curvilinear to a rectilinear structure' (E7) and the 'boundary conditions' (E6). E9 discussed the difficulties the team had to 'turn the roof to a wall'. Furthermore, according to A9, architecture was handled with difficulty when small cellular spaces had to juxtapose big spaces. E5, similarly, talked about the difficulties in juxtaposing 'the enclosed to the enclosing space'.

Respondents discussed the problem they had of handling a 'live' (A9) structure. A6 talked about the function of the building which dictated the form adopted and the difficulty of the public in accepting it. A2 explained that the form of the building dictated the behaviour of the user.

P8 was the least innovative building of the case studies –and A8 agreed that the degree of innovation it initiated was limited. E8 explained that it was an 'engineering predominant structure' and the architect came later to beautify it by adding elements.

1. 2. Planning, urban and environmental considerations.

Since some of the projects in question were tests of new ideas, contextualism and issues of adapting the building to the urban or other grain tended to be of less significance. Buildings like P2, which can be dismantled and change location, were typical examples of this category. When contextualism and issues of adapting the building to the urban grain were considered, the access to the building appeared to be difficult to handle. According to E5, the lack of surrounding buildings was a problem for P5. A7 described the difficult conditions under which P7 had to be adapted to the landscape. Difficulties in adapting the structure to the landscape were described by A6. In that particular case (P6) a minimal net was the answer.

Another issue discussed in this section was the response of curvilinear 'thin' structures to wind and snow loads. This was a concern for the design team and in the end required special measures in most of the case studies. Wind tunnel tests and computer

programs predicted the resistance of the structure to failure. Possible failure was a crucial source of risk regarding public safety.

Spaces enclosed and created by awkward shapes and thin membranes require special lighting and ventilation. In P5, ventilation was an issue the design team had to deal with for the first time, since there were no precedents of 'ventilating mechanically' a 'modern' tent of the size of P5. Lighting was an issue which concerned the design team, according to A7. Additionally, ventilation was difficult but challenging. The solution found was an innovation, to ventilate a two-layered fabric. In most cases, the lack of conventions regarding thermal behaviour and ventilation posed an additional difficulty for the team (A4).

1.3. Choice of material.

Two patterns were identified when the criteria to choose the material were discussed.

The one was based on 'availability, durability and economy' (E5), which is also the case with a conventional building. In such a case, innovation was not associated with the choice of material. The respondents explained that when the material was not cut to fit on site and had to be prefabricated, there was additional pressure on the design team to produce very accurate drawings.

The other consideration was to choose the material which best corresponded to the proposed structural type. A3 explained that 'the choice of material must be the result of a happy relationship of that material with the structure and not a result of aesthetics'. Moreover, it was suggested that the design team must be aware of the properties of materials and their behaviour under various loading conditions. The engineers in P4 had difficulties in handling the material. Anxiety regarding its possible collapse was an additional problem, since failure might occur with little warning. The performance of the structure of P4 was unpredictable. It was difficult to predict the properties of timber when wet and dry.

In respondents' accounts, the exploration of a new language and the properties of composite materials (teflon, etc.) seemed to have been both challenging and difficult. A5 and E5 found it hard to choose the material because the choice itself was an exploration of a new language. It was fascinating for E9 to cover long spans with minimum thickness. E3 pointed out that one of the problems was that the materials were chosen late. E6 described an extreme case in which the choice of material caused a debate. The suggested material was non-proven in use for a building. Generally, the material determined the form and, in effect, the structure of the case studied.

1.4. Buildability and design of details.

The design of details and the construction method to be adopted are discussed in the same section because, as A2 explained, details are the prerequisite to solving the problems of construction. Difficulties lay in the unknown technical input when details were designed. A2 described the difficulties the team had in designing details and tailoring the patterns. In P6, it was very difficult to design the details of the joints where the flexible structure met the gates. E8 explained the difficulties faced in predicting 'creep characteristics'. A7 and E7 talked about the difficulties the design team encountered in the design of details.

Findings from the first few case studies indicated that the design of details from first principles was inevitable. As E3 explained, that was difficult due the problem of estimating safety factors. However, when innovation was in the spirit of the group, design teams were very often inclined to design 'new' details just for the challenge, even if standard details could have been used. That was the case in P4 and P5. Teams which found it difficult to innovate when designing details found the existence of precedents very helpful.

Another problem derived from the fact that it was not clear which member of the design team possessed the knowledge for designing details, or who was responsible for doing it. The confusion was apparent in respondents' accounts. A5 and E5 valued the

contribution of the contractor as very significant when details were designed. A9 and E6 were quite satisfied with the contractors' intervention when the design of details took place. E6 said that the fabricator changed the details that the design team had proposed. A6 seemed to understand the importance of details, but stressed that this was the engineers' task. In some cases, the entire design of details was undertaken by the contractor or sub-contractor. In other cases it was unclear whose task it was.

Further, it was not very clear, what the method of simulation and resolution had to be when designing details. Many engineers believed that design should start with physical modelling and continue with computing. Only when the design of details is completed and accuracy is ensured should the construction start. Chronology seemed to be an issue in the interviewees' accounts. Getting the chronology (sequence of activities) wrong was one of the problems of P1, where, according to E1, erection started before the shape of the roof was finalised. E1 went on to place responsibility on the architect for further developing the architectural notions of building and detail. E1 explained that a physical model was used to make everybody understand the construction method that needed to be adopted.

Buildability was a struggle for the majority of the design teams. A construction method which was not well-thought through resulted in unforeseen problems on site. The respondents found that drawn construction details did not work on site. In A4's accounts, this struggle was apparent: 'There were difficulties in ensuring safety of construction method and stability....It was hard to determine the direction of elements and handle the flexible joints'. In P9, difficulty appeared during erection in handling the boundary conditions and stretching of the fabric. This was resolved with a technique proposed by the subcontractors; 'When the structure is not rigid, it takes time to make sure that these adjustments are right.' (E9).

E6 explained that inaccuracies in fabrication and erection have to be absorbed by adjustable details. This may mean that the details are expensive and the structure may

look inelegant and over-designed. In addition, the argument for utilising the minimum amount of material may not be valid any more. In A8's accounts it was suggested that 'the design team has to research, analyse and test alternatives, putting more emphasis on buildability'. E8 supported his viewpoint, attributing mistakes appearing during erection to the improperly worked out original idea, which he linked with the architect's responsibility for not understanding the importance of buildability.

Organisation of team building.

Architects and engineers are standard members of any design team. In many cases, clients become active participants. There are also new characters, such as consultant architects or engineers, proof engineers and contractors. The questions that emerge are: how do these people get together; what is the task of each individual; who allocates these tasks, and when does this happen?

2.1. Team roles.

2.1.1. The role of the leader.

Leadership seemed to be the most confused role in participants' perception. Groups which started off with an appointed leader seemed somehow to come to terms with his presence and develop two different attitudes. One was to respect and admire him. The findings suggested that these were the ones adopted by those who knew the individual from the past. They believed that he was in charge of allocating tasks and 'had the last word'(A2). The other stance was to recognise him as a leader but reserve the right to disagree with him. The team would often become frustrated when there was no way of imposing their own ideas.

There were three roles for the leader:

Firstly, a specialist who represented and looked after the interest of the client. He was the medium through whom the client and the design team communicated. In such cases,

accusations of favouritism towards certain members of the design team were noticed. The leader did not need to be technically knowledgeable or a specialist in the field of unconventional structures. The most important talents needed to carry out this task were well-developed communication skills and diplomacy.

Secondly, the leader was seen as the person who was the leader of the practice which produced the competition-winning scheme. In many cases, difficulties appearing during the design process called for the consultancy of another practice or that of an individual. The consultant was often seen as the person who could alleviate the difficulties and push the design process forward. The group tended to perceive him as the new leader, even though he or she had not been formally appointed. This led to conflicts between the leader of the existing but ineffective team and the newly introduced consultant.

And, lastly, the leader was seen as the 'emerging leader' figure. However, this type of leader was not concerned with communicating with the entire group but only with his immediate fellow designers who then conveyed his ideas to the rest of the team. In a few cases, leadership was associated with extremities of power abuse. The leader tended to view the group as his own possession and, in effect, he felt entitled to fire participants with whom he disagreed.

2.1.2. The role of the architect.

Four different types of architects emerged from the analysis of data.

Firstly, the architect of the competition-winning scheme, who would also assume the role as the leader of the group. In most cases this was an architect new in the field with virtually no experience, whose imagination and conceptual strength were the qualities which pushed forward their proposal. However, it was found that issues of buildability and feasibility were usually not well-considered and very often this led the design team into a dead-end. Subsequently, intervention of other parties became necessary. The architect's insufficient knowledge of technical issues made it hard for them to

understand the difficulties that would arise. In effect, quite often the new party suggested alterations to the original proposal, alterations which were often inevitable. Occasionally, disagreements over the possible changes bred ill feeling, since the nature of these changes conflicted with the original idea; often the architect's ideas were conceptually strong but technically weak, whereas the propositions of the party called in later were of a more technical nature. Thus, the architect's initial conception was challenged and there was always a sense of threat that the original recognition acquired by winning the competition would never again be enjoyed.

This type of architect tended to heavily rely upon engineers or consulting architects, but at the same time would see them as participants whose presence and involvement were not necessary from the beginning. The findings showed that such architects were imaginative, creative and not numerically oriented. As a result they favoured physical modelling and sketches, while they were not keen on computer simulation. They tended to believe that the design of details and the choice of structural type or materials was the engineers' task. Still, these was the type of designer who –lacking extensive technical knowledge– could encourage innovation.

Secondly, there was the architect-consultant type: The architect-consultant was the least clearly-defined figure with regard to the degree of contribution to the scheme. The nature of this contribution may have been part-time consultancy, in which case the architect was invited to solve a particular technical problem. Occasionally, the consultant would then have become a core participant and even a leading force in the design team. He was mostly empirical, challenged by risk-taking action and with vast experience in the field. It was found that the architect-consultant was indifferent to intergroup relationships and would seek out a certain circle of people he would be familiar with, so that his messages would be clearly conveyed. He relied tremendously upon his previous experience and favoured model-making techniques. He saw computer simulation as a means to achieve accuracy, and suggested that that should occur at the late stages of the design process. His perfectionistic urge seemed to agitate

the design team and delay the design process. There were extreme cases, as participants reported, where, in order for the building to be completed, the consultant had to be asked to leave the group. Wide experience in the field was at times accompanied by arrogance on the part of the architect-consultant. This, together with a possible threat of displacing the recognition and other rewards from the original designers, influenced the dynamics of the group, generating aggravation and confusion of roles.

The third type was the architect-assistant: This was the type of architect who was not involved in the conceptual stage but was allocated a specific role by the original team so that time could be saved. Previous experience in the field was not a prerequisite. The original team and the leader viewed this type as a disciple, not expected to take the initiative. He or she felt more secure working with the engineers from the beginning of the design process and recognised the contribution of the leader. At the same time though they also felt that their creativity was suppressed.

And lastly, the architect of 'embellishment' whose task was to add to the architecture of the building. In one particular case study the architect was invited to give consultation as to how the building 'could look' more interesting. In this particular case the architect's contribution was minimal and it seemed that the harmonious working environment and lack of disagreements could be attributed to the infrequent meetings of the design team as a whole.

2.1.3. The role of the engineer.

Three different types of engineers were identified. In most cases the engineer was invited to join the team after completion of the conceptual stage:

Firstly, the 'technical' engineer: This type of engineer concentrated on technical issues. In their accounts these engineers emphasised the importance of detailing for the feasibility and transition from a conceptual drawing to a construction drawing. Their task was of a numerical nature. They themselves believed that professionals of their

category are generally trained to follow rules. They attributed the problematic collaboration between architects and engineers to the quality of education the former receive. They considered themselves as rescuers of the design team and therefore expected recognition and rewards equal to those enjoyed by architects. They partly attributed the problems that appeared during the design process to their late involvement. They were practical and favoured the use of computers, after the conceptual stage. They explained that unconventional structures have a three-dimensional, sculptural nature which differentiates them from ordinary structures. In effect, as they stated, an ordinary engineer is unable to handle their design, unless he employs accurate three-dimensional geometry. This accuracy is ensured via extensive use of computers. They normally held architects in contempt and questioned the latter's ability to be realistic and executive.

Secondly, the type of the 'architectural' engineer: In most cases they started working with the architects from the very beginning. The whole group was assembled by the client or the architect –appointed by the client– who brought in the engineers. In their accounts, engineers of this type seemed to respect the architect and to be familiar with the techniques that the architect used, such as model making and sketches. They discussed issues of precedents and concepts, and seemed aware of architectural notions. They favoured visualisation in CAD. They seemed to understand role clarity. They considered that architects and engineers are of two different natures but that the design team needs both parties in order to be efficient. Mutual respect for a healthy working environment was considered essential. They seemed quite relaxed about taking calculated risk in order to innovate and found it challenging to work with innovative architects. They stressed very often the necessity for compromise and viewed disagreements as a healthy way to the resolution of problems.

Finally, the 'back room' type of engineer: this type of engineer acted as a consultant on a part-time basis. He had a very specific, analytical knowledge of the subject and in most cases he was numerically oriented. He was the key person in guaranteeing the

safety and resolution of the proposal, but he very often did not interact with the design team. Engineers belonging in this category were first involved at a fairly late stage in the process and did not take or influence any decisions at the conceptual level. However, limitations or difficulties often appeared after the analysis done by the engineer and those could alter the design and influence the decision making of the team.

2.1.4. The role of the client.

In all cases, it was in the interest of the client to control the cost of the construction and the time spent both on the design process and the construction. The refinement and crystallisation of the form of an unconventional structure was found to be an ambiguous, time-consuming process which made predictions on cost and time more complicated. Since there was often no fixed form, cost or time schedule, frequent contact with the client was necessary. Also, because of the ambiguous characteristics of these projects, many clients preferred to get closer to the action and become active members of the design team. In some cases, one of the tasks of the client was to allocate new roles.

Confident design teams found this involvement unnecessary, unless the client was sympathetic and encouraging with regard to the innovation. A discouraging, 'normal' client appeared to be a drawback in the design process, whereas less confident design teams valued the involvement of the client more. In terms of time saving, the presence of the client –which implied immediate approval or disapproval– was found to be useful. In most cases, visualisation became complicated when the design team needed to explain the scheme to the client. Physical modelling and three-dimensional images were found the most suitable means of communicating ideas to the client.

2.1.5. The role of the contractor.

The contractors in many cases became active members of the design team from early on. There were two alternative attitudes towards the contractor's involvement. In the

first case, groups with experience in the field or groups that saw innovation as an end in itself viewed the contribution of the contractor as a late, if not unnecessary, input.

In the second case, less experienced groups, who lacked confidence, valued and relied upon the contribution of the contractor. His presence in the design team from an early stage was seen favourably. In extreme cases, the contractor would undertake the overall design of details and even build physical models to gain more understanding.

2.1.6. The role of the proof engineer.

The proof engineer was introduced to verify the feasibility and the public safety of the proposal. The findings indicated that the role of the proof-engineer was a very delicate role because, while the responsibility of public safety ultimately lay with the proof engineer, he also had to be aware of the detrimental implication that disapproval had on a project. His task was often further complicated by the constraints on time and resources. In most cases, the decisions made were largely based on intuition and mutual trust between the proof engineer and the designers.

2.2. Individuals.

2.2.1. Education and nature of disciplines.

The lack of communication generally was attributed to education, experience and characteristics of individuals.

Many of participants found it interesting to work with colleagues for different backgrounds. Conflicting views regarding the necessary background of each were nevertheless frequently expressed. Some felt that engineers should not work on unconventional schemes unless they have an understanding of such structures. It was argued that understanding can be gained only if one works with the experts and pioneers in the field. A3 talked about the 'specific knowledge' or 'know-how' which is

necessary. E3 believed that communication in general was a problem of education across disciplines, and that individuals should respect each other for what they know.

Some participants believed that the architect of unconventional structures must have some knowledge of structural behaviour and a 'good feel for engineering' (A4). More specifically, it was mentioned that not every architect can handle the kind of geometry involved in unconventional structures. Similarly, E9 explained, even though it is a matter of individuals, 'the architectural education should develop a greater 3D sense and engineering'. Similarly, other participants believed that the engineer of unconventional structures has to have a 'peculiar' way of thinking and be inspired by architecture. E4 added that an 'ordinary engineer is not adequate' and that specialised engineers are needed for geometrical input.

In the respondents' accounts, the unclear notion of the influences that architectural and engineering schools have on the respective individual was evident. Architects and engineers cultivate different qualities throughout the course of their formal education. As E explained, 'architects love living in uncertainty. Engineers are more executive and rigorous. Architects are more intuitive, odd, and less decisive. Their nature is different too; ...' and he went on to discuss further the different nature of the roles of the two disciplines: '....there is a management role in engineering which does not exist in architecture'.

E8 genuinely believed that the relationship between architects and engineers is much stronger in the design of unconventional structures and all this starts because they are different in nature; 'the architect is excited by forms'. Lastly, E6 took a more mediating stance: 'to respect [one's] fellow-designers for what they are, [because] they are all equally important'.

2.2.2. Exchange of information.

Although the issue of exchanging information across disciplines was a general one, the information provided was associated, in most cases, with the experience respondents had with the project in question. For example, participants stated: 'I would do it again because of the fascinating experience I had working with these sensitive engineers.' or 'We had constructive discussions.' (A5).

The response to the question of exchange of information indicated three different directions:

i. It was argued that exchange of information is a matter of individuals who succeed or fail in getting this information across. As A2 explained, 'it is a matter of individuals rather than professions'. From E8's point of view 'There was perfect harmony and communication..... After all communication is a matter of individuals' .

ii. Respondents indicated that improvement of communication lies in the clarity and accuracy of the information exchanged; Quoting the respondents, 'the exchange of information depends on the architects who have to bring the concept to a discussable level before the engineers are involved In order for the exchange to be easy the architect must have a feel for structures' (A3).

iii. The problem of exchange focused on the unclear nature of projects and professions that interact; 'The role of the architect has changed with the engineering nature that structures have nowadays'. Here, communication appears to be understood as a matter of good will. Still there was evident confusion concerning roles and professions.

iv. For some participants disagreements were explained by the inherent differences between architects and engineers.

2.3. Means of communication.

In participants' accounts there seemed to be some confusion about the means the design team actually employed to discuss and exchange ideas amongst themselves or between them and the client. There was also confusion about the means of simulation of the architectural properties of the building. The issues seemed unclear, firstly because the same means were used in both communication and simulation, and secondly both of them happened simultaneously at times.

Physical and computer modelling were found to be the most popular, and were repeatedly mentioned by both architects and engineers. Other means of communication and/or simulation were hand-drawings and sketches, structural calculations, numerical analysis, three-dimensional geometry and verbal exchange of ideas. The following section will describe these various methods and their aim, as well as their advantages and disadvantages as understood by the participants of this study. The same section will pinpoint the discipline which favours each one most and the phase of the design process at which the respective method is usually employed.

2.4.3. Nature of means–aim, chronology.

2.4.3.1. Physical modelling.

This method was employed both as a means of communicating ideas among the design team and as means of simulation. The physical modelling of unconventional structure has a peculiar nature. The designers in the present study pointed out that an unconventional structure can be simulated only by employing unconventional techniques (chains, soap-bubbles, tights, etc.). In most cases model making was extensively used.

Different types of physical modelling were identified: i) the presentation models, used to communicate the concept to the client; ii) the structural models, which are rough models, and changeable so that structural behaviour and failure can be tested; iii) wind

tunnel models used to establish the wind loads on the building; iv) full scale models on which details or materials are tested.

Architects and engineers both agreed on the importance of model making. However, the majority of the former seemed to appreciate it more, and rely upon it, attributing its usefulness to the visualisation and directness which the method facilitates. The majority of the latter saw it as a means for the refinement of the conceptual stage, but even then only as an ancillary to computer means. They related its usefulness to the understanding of failure and simulation of collapse which the technique provides. Both disciplines found it extremely useful to be able to visualise the effects of changes such as the position of supports by physically changing the model.

In many cases the contractors make physical models to gain an understanding and communicate with the designers.

Even though physical modelling was seen as making a vast contribution to bridging the communication gap between architects and engineers, it was also understood to have pitfalls. Engineers stressed that its coarseness and inherent inaccuracy can lead to erroneous results. It was considered adequate for small scale projects, but misleading as far as big scale projects were concerned. Design teams using model making as the means of simulation seemed to need more than one model to test different aspects of the design. Model making was a costly technique of simulation, and, compared to computers, it was found to be time consuming. Furthermore, it appears that difficulties were encountered when scaling up the results of structural model tests.

2.4.3.2. Computers.

When the first three projects discussed in the case studies were being designed, computers were not widely available. Computer programs had to be written for each case. Even after writing these programs, difficulties appeared in interpreting the results, due to lack of graphic output. Nowadays, architects and engineers seem to favour the

use of computers. The majority of practising architects believed that they could operate computers using CAD to communicate their proposals in three dimensions to the client. They also believed that numerical analysis on computers was the engineers' task. A few architects seemed to believe that computers could substitute all other means of communication.

Two different points of view concerning engineers' beliefs about computers were stated. According to the first, computers can co-exist with model making and must be used after the conceptual stage. According to the second, computers are the perfect means of visualisation and communication across disciplines. Overall, the majority of architects and engineers argued that computers must not be the only means of communication and visualisation used.

Computers aid visualisation of complicated three-dimensional proposals and 'three-dimensional intersections'. They are accurate and can carry out complicated calculations. In the first three projects of the case studies, computation had previously been time consuming. Nowadays, computers are considered a means of saving time. In the case of P7 and P8, computers were used on site to finalise the design. The majority of engineers considered computers appropriate for the design of details, structural analysis and calculation of geometry.

2.4.3.3. Hand-drawings, sketches.

It was seen as a new departure for architects to give priority to physical modelling and computers instead of hand-drawing which is the traditional means of communication. Hand drawings still play an important part, but as ancillary to the other two. In most cases, the reason given was the difficulty of accurately representing three-dimensional curves by two-dimensional means. Similarly, it was argued that perspective drawings, are difficult to make, time consuming and misleading. Although sketches are generally quick and can reflect the designer's aspiration directly, engineers found it difficult to emulate the free-hand drawings of the architect, if these were the only input provided

by the latter. Architects seemed to be in favour of hand-drawings possibly because sketching was a skill they had developed during their training, unlike engineers who had not been trained to sketch. Spontaneous hand-drawings possess a certain quality that the hard line of computer drawings, which are constructed with calculated accuracy, do not. Hand drawings reflect the thought pattern of the architect and the way he or she visualises the building in three dimensions.

Architects argued that drawing needs to precede model making. Engineers, on the other hand, argued that drawings are not reliable for geometrical decision making. A number of them supported the view that hand-drawings are inappropriate for unconventional structures, because they are unable to represent three-dimensional intersections. Some of the designers emphasised the advantage of the directness of hand-drawings, where each line represents more than the fixed location in three dimensions. Even though hand-drawings cannot be taken as construction drawings, 'there is something about the physical contact, between the mind and the paper, which is the link; the hand' (E7).

2.4.3.4 Structural hand calculations.

Architects who used empirical methods like physical modelling, and were experienced in the field, were at ease with simple calculations which helped predict the behaviour of a small scale unconventional structure.

When the scale of the project was big, complicated structural calculations were used, often involving complex computer programs. The use of computers goes some way to ensuring reliable structural calculations. In the case of P1, P2, P3 and P4, special computer programs were written and technical papers were published in learned journals.

2.4.3.5. Three-dimensional geometry.

There was an extensive discussion about the difficulties the design teams had in tackling the visualisation of complex curves and three-dimensional intersections. E8

pointed out that the conceptual stage must be resolved by understanding the geometry of the structure. For Sydney Opera House, as E1 explained, the design team had to produce 'geometrical drawings', emulate geometry, and analyse the structure on computers. One of the reasons why physical modelling was considered as an important means was the understanding the geometry offered. Engineers extensively referred to system points and surface geometry, an issue which is discussed in appendix 5.

2.4.3.6. Discussions and 'language'.

When communication and its means was raised as an issue, the majority of the engineers mentioned 'discussions' as a means of communication. They accused some of their fellow engineers of using 'jargon' to confuse those from other disciplines not familiar with their terminology. E9 illustrated the point by saying that 'the engineer should try and work hard while being able to use and describe physical phenomena in a very simple language'.

6.2.3. Strategies for design process and team management.

Two general suggestions were identified in respondents' accounts. The first referred to the 'ingredients' of the introduced innovation, and the second referred to the design process and its improvement. Further, these issues were related to the organisation of the group and the means of communication. Thus:

- i. The experience of designing an unconventional structure gave the team confidence to innovate, gaining a better understanding of what the limitations were. Moreover, the circumstances had to be appropriate to encourage an unconventional project to be completed. There had to be enthusiasm for the novelty and determination to achieve a successful result: 'Everything one can imagine is possible.' (A6).
- ii. Interviewees stated that a lesson one could draw from the experience of designing an unconventional structure is how to contribute to its evolution and/or the design of

details. That can be more easily achieved when one moves step by step from smaller to larger scale projects.

iii. Young designers were advised to learn by observing and listening to others, and by working with the pioneers in the field. That would help them to learn from others' mistakes. The necessary ingredients for innovation were considered to be imagination and 'bravery'.

iv. Future designers were advised 'to find the right individuals one is going to work with'. An efficient design team 'does not depend on known organisations, but on individuals'. This organisation is more effective if engineer and architect 'are seen as equal partners'. The option to choose the client was considered an advantage for the organisation of the design team (A).

v. One should research, analyse and test alternatives, (A8) be conceptually strong when designing 'these structures' (E8) and use all kinds of models (computer, physical, etc.) (E6).

6.2.4. Intervening Conditions.

Time and cost.

Often the design and construction process was delayed and the cost overran. Time pressure and limited budgets affected the atmosphere in which the design team operated, as well as the resultant building.

Time.

Delays and the spending of too much time on certain aspects of design or construction were attributed to various causes. Often the design team was unable to predict the time and cost of design, manufacture and erection. Thus, in most cases, time was overrun. In many cases, the design process went on until the building was completed. Time pressure seemed to be an additional source of stress for the design team. In effect, time

pressure often led to a hectic design process without phases. At times, this same pressure left no space for disagreements. E1 explained that the design process of P1 could have been cyclic as usual but, due to time constraints, analysis and exploratory research in materials and techniques, it happened in parallel.

A3 added that uncertainty was caused by the unclear sequence of steps that the design team had to take during the design process. Some participants related time wastage to the delayed allocation of roles. Furthermore, difficulties of the design team were attributed to delays at the decision-making stage, and /or the delayed interaction of architects and engineers. Other participants stated that, with more time spent on the design process and decision-making stage, the process could have been better resolved. For some participants, limited time was an obstacle to familiarisation between individuals.

In contrast to the majority, where time constraints were seen as adding stress or causing problems to the design process, unlimited time could have led in some cases to indecisiveness. E3 and A7 explained that, if the consultant had stayed with the team till the end of the process, they would never have finished, as he wanted more time to elaborate. Some participants believed that unreasonable time spent on the design process, led to over-designed structures.

According to some respondents, the peculiar nature of the structures caused delays. As E4 explained, complications were caused by the peculiar nature of the structure. That led to a great deal of time spent on verification. A9 explained that the duration of the design process and construction are usually longer in a 'non- rigid' structure because the design team has to make sure that the 'adjustments are right'. A6 found the design process longer overall and the design of details more time-consuming than in normal projects. Time on the same project was spent on discussions with the planning authorities, negotiating the feasibility of the proposal. Another cause of delays described by E5 was the need to import materials on site, due to lack of availability.

According to E1, the resultant building (P1) could have been more elegant if more time had been spent on the project. Lastly, a word of caution was expressed: the designers should not commit themselves to certain decisions too quickly, even when there is time pressure (A).

Cost.

The budget for any given project can be split into design cost and construction cost. In the field of unconventional structures it was found that physical modelling and numerical form-finding with computers add to the cost of the design process. Moreover, the presence of the engineer from the first stage of the design process or the introduction of a specialist inevitably means extra expenses. Often, conflicts were associated with money when innovation was introduced. The interviewees stated that the engineers must be appointed from day one and architects must come to terms with the fact that they have to share the fees equally with the engineer.

As far as construction was concerned, the peculiar nature of an unconventional project and lack of experience often prevented accurate cost estimation. Most of the designers seemed to have come to terms with the difficulty in estimating the cost of a long-span structure. Some respondents even claimed that, in order to innovate, economy must not be an issue.

The implication for the cost of importing material which was not available locally was also mentioned. Teams who managed to be consistent with their initial cost estimate attributed this to previous experience and the input available from precedent buildings.

It appeared that the atmosphere of the design process can be unsettling if there is uncertainty about the success of the innovation introduced, taking into account the amount of money spent. E described such a situation in P1: 'It is the implications that the inherent uncertainty of unconventional structures has for the design team who faces

the dilemma to stop or to carry on considering reputation and money invested'. Furthermore, limited budget was part of the reason why P5 has remained incomplete.

Problems in the design process and their solution.

A wide range of problems was reported. Three patterns can be identified, classified according to the respondent's participation and position in the group.

i. Confident participants with experience in the field discussed issues of inefficient organisation of the group as the source of problems. In their accounts, it was argued that the design process is problematic when participants are not acquainted with one another, and/or if they have not worked together on past projects. As for young designers, it was suggested that one has to work with the pioneers in order to gain understanding and experience from them. Problems may arise when the special groups have difficulties in their collaboration. These 'special groups', A4 suggested, must be formed after the crucial decisions are made and each group can elaborate on the subsequent issues which emerge.

ii. Participants who were not given the chance to contribute significantly to the design process had different views of the group organisation. The problem was focused on their feeling of being dominated by either the leader or other senior members of the design team. A5 reported that he could hardly tolerate the leader: 'you do not do it [participate in such a process with an imposing leader] again'.

iii. Participants who fall into an in-between group, regarding their degree of experience and contribution. Their accounts were focused on technical issues of construction, feasibility, detailing and so on.

A3 experienced difficulties when trying to convince the client and the proof engineer about the feasibility of the scheme. E4 explained that nobody understood the 'buckling problem' and the possible risk. E5 encountered problems connected with the environmental control of the building. A6 thought that each detail of the building was a

problem, such as the boundary conditions. E6 found it hard to minimise the structure and adapt it to the landscape. A7's problem was to discover the appropriate construction method: 'One [problem] was to find the right idea, and then to make it feasible, in a way that a very organic building will be built according to measurements, grids, access, geometry, order'. E7 pointed out that the problem was to emulate the geometry of the computer drawings. Time pressure was the problem for A9 and user satisfaction for A2.

6.3. Conclusions-completion of the 'story line'.

The difficulties which appeared during the design process were attributed to the 'peculiar' nature of the projects and the implications and alterations that this nature imposed on the design process. The findings revealed no clear line of demarcation between architectural and engineering considerations. As far as the qualities of the team are concerned, two types of teams emerged:

i. Designers who saw innovation as an end in itself. This category of designers often possessed an exploratory nature, and seemed to enjoy risk taking. They were confident enough to invent solutions and were able to change their decisions to satisfy their quest for innovation. They often developed an arrogant attitude towards the ordinary client and were selective in that respect. The end result did not usually derive from a brief but from deliberate thought and an urge to innovate. They preferred working with people they knew and placed more emphasis on experience as the prerequisite for the efficiency of the design team. In their opinion, 'ordinary' designers were not adequate and the presence of specialists was necessary. They seemed to appreciate role clarity, respect a skilful leader, and recognise him as the manager of the group organisation. Interestingly, they tended to be loyal to 'traditional' methods of visualising and communicating unconventional ideas. They used physical modelling (for example stretched tights as flexible membranes, etc.) quite extensively and many of them saw computers only as a means of saving time and ensuring accuracy.

ii. Designers who saw innovation as a result of a complicated brief which required a long span. In this study, the designers falling into this category showed a lack of confidence. Although they had been involved in the design of an unconventional structure they did not admit that special knowledge, previous experience, and familiarity in the group were necessary for the first time. They were prepared to take risks, while at the same time they were frightened of the implications for public safety or partial failure of the building. For these designers, the issues at stake were the responsibility to the public, their professionalism and the reputation of the individuals and the group.

They found the presence of the client quite essential and especially his or her reassurance and support. They often did not comprehend the necessity of the leader and tended to disapprove of him or her as imposing and patronising. Innovation was encouraged by their ignorance and blurred perception of risk taking. It was not very clear what the preferable means of communication and visualisation was, but it seemed that computers and physical modelling were the most popular, having equal importance while serving different purposes.

Generally, strong subjective views were given by the participants as to their understanding of the organisation of the group. It would be a myth to believe that designers were neutral and disinterested actors when they engaged in design. The professional actions of designers were essentially 'political' in character. By that it is implied that designers engaged in political manoeuvres when there was promise of success, recognition, fame and so on. These activities cannot be understood as unfortunate lapses by otherwise disinterested designers, but as vital aspects of the design process.

The design process was imbued with controversy as far as the chronology of means, activities and participation of individuals was concerned. Subjective explanations were given as to the advantages or disadvantages of means of communication and

simulation, depending on the nature and educational background of individuals. A flexible attitude using all available means seemed to be the most sensible approach. There was controversy regarding the usefulness and the capacity of model making, computers and three-dimensional geometry.

It was clear that simultaneous involvement of architects and engineers, and openness to accept consultation by specialists was seen as necessary. That, of course, would have implications for the size and, therefore, the management of the group. It was suggested that the group should comprise individuals of all natures ('analytical, practical, skilful in design, specialists in buildability').

Education was not generally considered to be one of the causes of communication difficulties. It was implied that unconventional schemes require a special way of thinking, flexibility of brief, early choice of material and careful and thorough design of details. Flexibility of brief and freedom to allocate time and cost were seen as positive or even necessary ingredients for the evolving design process of the case studies.

Overall, interviewees appeared to have their own personal 'theories' which they were able to ground well. It must be noted that the ability to draw general patterns/conclusions, should not be taken to imply that all respondents viewed the 'problem' or its 'solutions' in the same manner. Based on the present findings, the way each person understands the difficulties of the design process cannot be adequately understood by simply examining general dimensions. On the contrary, it was found that each interviewee had his or her own way of interpreting the problem and his own modes of grounding the experience of the design process, so that, in the end, each person had his unique 'contribution' to make towards gaining some insight into the design process of unconventional structures.

Chapter 7. Explication of Emerging Themes: Group Organisation and Means of Communication.

7.1. Introduction.

The findings in the two previous chapters indicated that other issues apart from issues discussed and included in the story-line appeared repeatedly. These other issues were not clearly connected to the core category, and were also not sufficiently explicated. This chapter will attempt to explain a number of unexplored issues which were repeatedly found to be present when analysing the data. The issues were the importance of group organisation, three dimensional geometry, computer programs which simulate unconventional structures, and unconventional physical model-making techniques.

At this stage of the thesis, further reading and research was necessary in order for the emerging themes to be filled in. As Strauss and Corbin (1990) have suggested, the completion of these themes maximises the generalizability of the Paradigm Model.

7.2. Organisation of the group.

In this section issues concerning the organisation of teams designing unconventional structures are discussed. It would be somewhat arbitrary to attempt an in-depth investigation of these issues, firstly because this is not a field in which the researcher has specialised, and secondly because this is not the ultimate aim of this thesis. However, reference to the basic principles and theories of Group Dynamics (as it is called in the area of social psychology) was considered necessary, so that interpretation of recurrent phenomena would be possible.

It is hoped that some generalizable explanations will be given to the 'social' phenomena of the design process of unconventional structures. It is further hoped that these explanations will increase designers' awareness of the possible difficulties encountered in the design process of unconventional structures. As Belbin (1981) has explained, the

team has to be aware of possible strategic mistakes at the team building stage; 'the more conscious they are of where their strengths and weaknesses lie, the easier it is to adjust to that information. The lower the awareness, the greater the danger of making strategic mistakes that spring from self-delusion' (p. 92).

In the present study, the groups in question consisted of designers and other participants who influenced the decision-making. The groups were assembled on the occasion of the design process of a particular unconventional project. A public building, with a specific use (stadium, exhibition centre, pavilion, etc.) is very often the outcome of an international competition. The expectations from a winning scheme lie in the fulfilment of the brief and the originality of the ideas behind the scheme. The criteria for judging a scheme are not clearly defined but the innovation attempted could be associated with the use of a new material, a new structural type, or the roofing of a long span. The task that the design team has to undertake is a difficult one; the objective in most cases is to cover a long span, column-free space, employing an unconventional, non-trabeated structure. Thus, the winning architectural practice needs the professional advice of an engineering practice. The size and the genuine architectural-engineering nature of the project generates difficulties. This is because it is large and public, and is usually situated in a prominent location.

The design team will undertake the metamorphosis of proposed ideas and concepts into a finished product. The team are the members of the winning architectural practice and new members who will join in to contribute. The size of the task demands an increase in the number of 'hands' available and the nature of the task requires the contribution of individuals with specific knowledge. Engineers are introduced at the stage of design team building and it is the nature of the project that changes the secondary role of the engineer to a starring role ("This was a very close cooperation between architects and engineers which I never experienced for any other structure" E3). This fact carries a great number of implications for the design team structure, and the working environment of the group. In other words, the structure of the group changes when the

significant input on the part of the engineer or the specialist places him or her in a leadership role, which the architect would have otherwise possessed. In conventional structures, and before the role of the project manager was established, the architect tended to be the leader of the design team, and the structural engineer would be the consultant.

The confusion generated as to who the leader should be –the architect or the engineer of the project– is reinforced by the prejudice that may have been cultivated during the individuals' education. Glen (1975, p.27-28) associates the power and influence of prejudice –either hostile or favourable– with the effectiveness of the group.

The majority of participants, including the pioneers, believed that architects and engineers have different, but nevertheless interdependent and interrelated roles. It was found that only few believed that the architects' and engineers' objectives were conflicting, and, because of that, problems are likely to appear during the design process.

Another way of looking at the interrelated objectives is the common desire for the production of a safe building. In many cases the structures are experimental and tested for the first time. Apart from safety, the implications of possible failure for the reputation of the professionals involved are huge. The working environment of the design team may be affected by the difficulties that arise. Following the opinion of Zander (1971, p.382) it is quite common for the group to have to face situations when difficulties arise, in which case an extreme 'ego-threatening' position could occur for individuals. The group members experience task-related tension which is however reduced with task completion.

Failure would affect all members of a design team. Therefore, because the end result is influenced by the objectives of the different disciplines involved, these have to be interrelated and interdependent. The connection between the failure of the group and the individual's embarrassment agrees with Zander's (1953) theory which suggests that

group members are primarily alert to the unfavourable consequences from group failure, humiliation, derogation, and costs linked to failure. According to Zander, what group members wish to avoid is not the failure itself as much as the embarrassment following failure, “The problem from the engineering stand point really is that the decision to go ahead was made on trust to a large extent and potentially they there could have been an awful lot of egg going on a lot of people’s faces so in a sense that was the problem; the problem was the fact that potentially the things could have gone wrong, but they didn’t” E4). Zander called this motive ‘a desire to avoid group failure’ (p. 421). Humiliation is even greater when the group fail to complete an easy task rather than a difficult one.

The findings clearly showed that an unconventional scheme is not only innovative but is also risky. That could probably explain why the leadership role was found to be blurred (“but for long span structures I think there are in-between buildings where the architect has to be the leader and it is very clear for bridges for example the engineer has to be the leader [.....] I think these long span structures are in between” (E3). In other words, individuals do not wish to act as formal leaders of a group which introduces innovation, which is a risk-taking action with an unpredictable or unsafe future. It is obvious that, if the success of the project could be guaranteed, all eligible participants would be equally happy to act as leaders and hence gain monetary and other rewards. However the task may be associated with failure, an element that discourages participants from taking the initiative and major decisions. Zeisel’s (1981) theory has further suggested that, “in making a decision, people weigh what they think are the possible effects of the decision against the risks of unintended consequences” (p.52).

The risky and unknown nature of an unconventional scheme and the importance placed on leading figures affects the decision making process. Laboratory findings in similar situations have discussed the concept of “groupthink” and “group polarisation”. The former is defined as a failure of members of the group to express their views due to the power of the leader. On the other hand, group polarization occurs when groups make

more extreme judgements than they would have done as individuals (Baron et al. 1992).

Not only can groupthink give the erroneous impression of consensus being present, but it may also produce poor group decisions or, worse still, may lead group members to support extraordinarily ill-considered policies. As for the concept of group polarization, research has shown that group polarization occurs through processes of social influence. These processes have been distinguished according to the nature of the topic involved. Hence, 'informational' influence (related to modes, persuasive arguments) is more likely when the task concerns factual issues (Isenberg 1986). "Normative" influence (competitive process triggered by knowledge of other positions) is more likely when the task concerns values, tastes and preference (ibid). Normative influence has also been associated with ego-involving situations, or situations or topics with a greater than normal degree of ambiguity.

In summary the issues raised concern the distinctive nature of the task and its implications for the roles within the design team, for the effectiveness of the group, its size, and for the working environment it generates.

7.2.1. Nature of the task.

The case studies indicated that the steps taken by the group members in order to reach their goal, and the contribution of individuals to the process were not clearly defined. Glen (1975) has suggested that it is necessary for any organisation to state clearly, 'what the purpose or goal of the activity may be, to identify and define the steps by which the goal is to be reached and decide what the individual contribution to the process should be' (p. 35). In his opinion, the efficiency of group organisation can be explained in those terms.

Shaw (1971) defines a 'group task' as what must be done in order for the group to achieve its "goal" or "subgoal". In our case, the design process corresponds to the

group task and the resultant building corresponds to the group goal. The group goal is an unconventional building; it is thus a complex goal, and, as it was found, the design process (group task) is unclear. The design process can be considered a production task because it requires the production of ideas, images or arrangements. It is also a discussion task because it calls for the evaluation of issues, and it is at the same time a problem-solving task because it requires the group to determine a course of action to be followed to resolve some specific problem (definitions given by Zander 1971, p. 370).

The nature of the group task –the design process– is unclear with regard to the sequence of activities taking place and the roles of individuals (“with non-conventional structures it is a lot less clear what the different roles are and particularly since the design of these sorts of structures are not taught at the university” E4). Cartwright and Zander (1953, c) have associated group and task clarity with the effectiveness of the group. The determinant of the effectiveness of the group, they explained, is the extent to which a clear goal is present. In the present study, it was found that the objectives of individuals differed in the way that innovation was seen –an end in itself or a need for a long span solution to satisfy a brief. In the opinion of Cartwright and Zander (1953, b), lack of goal clarity and effectiveness in achieving the results lead to personal dissatisfaction of members and low group morale.

The lack of clarity of the task is associated with the lack of information which could encourage communication amongst participants. Higgin and Jessop (1965) have addressed this issue explaining that: ‘communication difficulties lie behind the nature of the relationships between the communicators, and any attempt at improvement, however limited, cannot hope to achieve any significant degree of success in the absence of much more information than is at present available, about just what job any communication is supposed to do’ (ibid, p.35). Regarding the “information at present available” the findings of the present study supported the point that innovation was coupled with lack of precedents and national or international standards.

In many cases, respondents explained that the unclear, complex task led to “task irrelevant processing”, which Wilke and Knippenberg (1988) have characterised as more harmful for a complex than for a simple task. The reason they gave was that “a complex task demands the individual’s undivided attention, and, therefore, any attention paid to non-task factors (e.g. worrying) leads to poorer task performance” (ibid, p.323).

The possibility of failure alters the function of a large group and Zander’s (1971) theory appears to agree with the interviewees’ accounts in the present study. The possibility of group failure was reduced by the group’s strong desire to succeed. Past failure in the history of the group and the position of the individual members in the group were determinant factors in that direction. Thus, failure or success was associated with individual feeling of being attracted to the group, and the role which individuals possessed within that group. Ultimately, it was associated with the perceived consequences of failure, as explained earlier. However, Zander (1971) has suggested that, when the quality of past performance is unknown or ambiguous, group members cannot adequately estimate the probability of success or failure; hence, their choice of task will be influenced primarily by incentive values. Therefore, the level of aspiration should be higher in cases where past performance on similar tasks is known than in cases where it is not. In the former instance, the challenge of managing a relatively difficult task often leads to the selection of that task (ibid, p.357).

Raising the issue of attraction, the individuals are not only attracted to a group with successful history but also to individuals comprising the group (“of course you know people, you know friends what they can do, where their skills and weaknesses are, and then you can try to bring them together.” (A)). This idea agrees with Newcomb’s (1953) theory on the formation of groups. Individuals are happy to associate themselves with people whom they ‘like’ which, however, is rare at a professional level, or whom they prefer to work with, because they are motivated by the ‘reward associated attitude’. In general, individuals approach or avoid others depending on

whether it is seen to guarantee rewards or not. In this study, ‘perceived knowledgeability or expertness’ were sources of reciprocal attraction among individuals (“A7’s contribution was more than that because he was part of the design team and he is a good designer” (A7)).

The practices studied in this thesis were not multidisciplinary and a number of them were formed for the first time specifically to work together on the projects in question. In cases where there had been a successful past collaboration, teams were formed with this as the prior criterion (“what was of course very important was that I knew both E8 and A8 because we both worked together in times past, so it was a perfectly good personal relationship between the three parties, so it wasn’t three competing parties, so we had a perfect basis for designing something without feelings of jealousy or competitiveness” E9). Belbin’s (1981) theory has suggested that the reasons why teams are unsuccessful can be found either in the culture of the group as a whole or in the unfortunate combination of characters. In the case of non-multidisciplinary teams, the second appears to be the primary reason.

The fact that any group consists of individuals with unique characteristics and idiosyncratic ways of behaving (Shaw 1971; Glen 1975; Belbin 1993; Baron et al. 1992) must not be overlooked (“I think that A6 is the only one in the team that thinks he is the star, this is a problem anyway” A6). In a specific field like the one of unconventional structures, it is quite common for a person with special knowledge of the goal-task to be expected to use this knowledge to help the group achieve its goal (p. 167). As mentioned, the ‘peculiar’ and often unknown nature of the task imposes alterations in the structure and role attribution in the design team. Thus, the person with the special knowledge, not only helps the group to achieve its goal, but, being the only one with this knowledge may become the leader of the group. Shaw’s (1971) theory that the knowledgeable member emerges as the task leader was supported by findings (“LA P3 was the one expert that had done similar structures in the past at that time and that was the reason why he was asked. At the time it was already the experience of

[another tent] and this was the time that LA'P3 was asked as an expert. It was a long development that finally it was decided that it is buildable" (E3)). Glen (1975) more specifically talks about the power of the emergent leader to 'possess knowledge, skill or expertise which is in demand in that context' (p.38-39).

The idea of an emergent leader who behaves in a more authoritarian manner than an elected or appointed leader also agrees with Shaw's (1971) theory. Fodor (1978) has further suggested that, in stressful situations, like the ones this thesis explores, leaders tend to behave in a more authoritarian manner. Belbin (1981) stated that only occasionally is the leadership in successful teams firmly in the hands of a 'superstar' (p.102). This was not supported by the present findings where the leader was often a 'prima donna', a recognised figure in the field. In many cases the emergent, knowledgeable leader was disliked by his less powerful fellow designers. This was supported by Shaw's (1971) theory in which it is explained that the powerful person "is not seen as an attractive person for social interaction, not as attractive as less powerful group members" (p.298) ("Oh, we had a lot of disagreements, a lot, it was very hard but I enjoyed very much to meet E6 and I think we had a good relationship, and I am very happy with that, because with LA'P6 [the leader] it was not so happy. I had a lot of problems" (A6)).

7.2.2. Size of the group.

On the one hand, the size and complexity of the project warrant a large number of participants who bring their skills, knowledge and abilities and add to the 'hands' available. On the other hand, large groups encounter problems due to their size. This agrees with Shaw's (1971) theory concerning large groups. Organisational problems become more difficult as group size increases (p. 168). Large groups are necessary to carry out the task, but ironically this is when communication becomes more difficult ("Sometimes it was not necessary to explain what they have to do, it was really a psychological joke, to say that you are a good man, please do this or that, they had no

idea about that, but they should be a group, they should work day and night, because the time was very short, and we made several groups” A3).

The effectiveness of communication also depends upon the group task, the group composition and other factors. Thus, the larger the group, the less opportunity each person has to participate in discussions. Additionally, Grzelak (1988) has suggested that group members feel greater threat and ‘greater inhibition of impulses’ when participating in larger rather than in smaller groups. In line with the above, the findings demonstrated that the management of the team and the sharing of labour is indeed easier when large groups are divided into subgroups (p.297). And yet, the potential for conflict is greater in subgroups. That also justifies Shaw’s (1971) suggestions regarding the subdivision of large groups into smaller units. Glen (1975) has further proposed that the management system should be widely dispersed and individuals ‘who form the bridge between the groups [and] are described as “linking pins” (p.53).

The advantage of large groups is that innovation and genuine ideas are encouraged to a greater degree. That is attributed to the fact that individuals tend to support risky ideas in a group discussions because of the “distribution of responsibility arising from knowledge that others are participating in the decision” (Cartwright and Zander 1953, c) (“I suppose there must have been people thinking that, if things went wrong, there was always somebody else to blame. There must have been some of that I assume. People saying things on the record, that if things were wrong they can say ‘Oh, look I told you so’ that sort of thing must have been going on to a great or lesser extent” E4). Greater tension is released due to anonymity in large groups. Diffusion of responsibility is the characteristic of large groups which encourages risk-taking actions (Shaw 1971). However, as size increases the level of disagreements and the antagonism towards others was greater. Additionally, members felt less responsibility for helping when more members were present.

Further, Shaw (1971) has claimed that “members of larger groups are less attracted to the group, experience greater tension, and are less satisfied” (p. 171). That is attributed to the minimum opportunity given to each member of the group to express his or her opinions, the increasingly dominant role that one or more selected members play in the group, and the increased difficulty of maintaining interpersonal relationships. That agrees with Higgin and Jessop’s (1965) as well as Glen’s (1975) theory that ‘there will be an asymmetrical distribution of satisfaction of needs among members who do not share the same value system’ (p.91-92).

Note that the issue of time is also associated with the difficulty of task. Time was found to be a pressure for most participants in this study. Cartwright and Zander (1953) believe that there is an analogy between the time consumed and the perceived difficulty of the task. The authors link the task difficulty to the amount of effort required for task completion. Studies of task difficulty have revealed that, apart from the increase in time required, errors are also likely to increase (p. 369).

7.2.3. Group norms.

According to the literature (Shaw 1971), group norms provide a basis for predicting the behaviour of others and thus enable individuals to anticipate the actions of others, and prepare an appropriate response. However, the findings showed that individuals with specific knowledge in the field deviate from group norms. Hollander’s (1958) theory has suggested that this phenomenon is quite common and even allowed, taking into account the contribution of members to group goals in the past. According to Hollander, these members build up ‘what is called an idiosyncratic credit’ (ibid).

Role clarity was a problem in most of the cases studied. One possible explanation can be found in Shaw’s (1971) conviction that role clarity is associated with the permanent or temporary nature of the team: ‘the behaviour and influence of group members is a function of their roles in the group, and the impact of the roles is much stronger in the permanent than in the temporary groups.’ (p. 289). A design team has no clearly

delineated structure, especially when the members do not belong to a multidisciplinary practice. On the other hand, a multidisciplinary practice may reach conformity much more easily than a randomly structured design team. According to two of the most prominent researchers in the area of Social Psychology (Asch 1951; Milgram 1964), conformity leads to loss of individuality, restriction of creativity and reduction of all group members to a level of mediocrity (“The design team was quite peculiar, because A5 was acting as the professor and we were the scholars” A’5). Other researchers emphasise that conformity is also necessary, because it introduces order and helps the coordination of the group (Berkowitz and Daniels 1963).

7.2.4. Influences from other roles.

The effectiveness of the group depends upon the availability of the necessary resources, whether these are economic, material, legal, intellectual or other. Shaw has talked about the ‘complementarity of needs’ in a team (“you are talking about collaboration between individuals essentially. That is where the skills of the various individuals need to complement each other in the right way, that applies within the disciplines as well as in the sense that amongst the engineers we need say three or four people each of whom brings their own skills and the same would apply to the architects” (E4)). Belbin (1992) refers to necessary and problematic roles in groups. In the present study it was found that “the completer-finisher’s role seems to be important for unconventional structures due to the importance of details: poor finishing qualities were associated with individuals who tended to have a cavalier attitude to detail and low regard for obligations” (Belbin 1981, p.73) (“I think, it is a weakness of LA’P7, LA’P7 gets very nervous, in fact, I like LA’P7 very much but he gets very nervous when projects are going to site, you can look at things in models and you can look and study things, but you go to site and then it becomes exposed for everybody to see, the model is not going to ..., he gets very nervous and I understand that the same thing happened during another project, and LA’P7 was incredibly nervous that the thing would not be successful, he just got nervous as the thing got more complete” E7).

In the present study, the leadership role was often undertaken by specialists and this led to dissatisfied groups. In addition, Belbin (1981) has further explained that often, where specialists have risen through their speciality into management, “in spite of their advancement they were still prone to act like specialists, failing to take a rounded view of the problems confronting them” (p.84).

In large design groups, there will be participants who add to the ‘hands’ available for the completion of the task. Belbin(1981) has explained that there will be team members with no team role; ‘it is simply that some individuals do not fit at all well into any team’ (p.86).

7.2.5. Client’s intervention.

The dynamic involvement of the client was found to determine the status of some individuals in the group (“I think the big part of proposing the details is sitting down and discussing things. I had full confidence in the client to dispute the detail the engineers are proposing for the double plate of the membrane joint. I wouldn’t have built the building without the support of the client and that support develops from confidence. I said that I didn’t like that and he asked me what I liked, but I didn’t know what I liked” (A7)). Shaw (1971) has pointed out that it is possible for a source outside the group to cause changes to occur which will affect the relative status of group members (p. 266). Further, the presence of the client in some cases was seen as positive (“The client was very involved in the job, really understood what was needed. The client participated with us. The client was living with us [....]. Often if you have a good client it is actually a positive benefit because they are party to the decisions and you share them, with a good client you make a better building” (A9)). This contradicts the point made by Shaw, according to which the presence of others may be destructive when a person is performing a task. Thus there may be tension, caused by a person’s effort to attend to the task and destruction at the same time. Wilke and Knippenberg (1988 p.318, 323) have further suggested that ‘the presence of others may lead to

impaired performance' (social inhibition was generated if subjects were engaged in difficult tasks).

7.3. The means of communication.

According to Shaw (1971), one of the determinants of the effectiveness of a group is 'the degree of conflict among members, concerning means that the group should employ in reaching its goals' (p.345). In participants' accounts there was frequent reference to the use of computers and physical models as means for either simulation and/or communication amongst disciplines. All participants engaged in the debate concerning the controversial issue of the nature of these means, the advantages and disadvantages of using each one and the appropriate time each means should be introduced in the design process. Differential, three dimensional or surface geometry were terms used when description of the computer programs took place (Struik 1950).

The researcher attempted to familiarise herself with issues concerning differential geometry, computer programs and physical modeling. The difficulties with differential geometry, as expected, lay in understanding the mathematical notation as opposed to the physical concepts. However, it was interesting to grasp the relationship between curvilinear structures and the sophisticated concepts of the geometry of surfaces.

The computer program produced by the researcher is based on the same principles as those in the highly sophisticated computer programs used in engineering practices (Wakefield 1986). By far the greatest effort in writing a user-friendly computer program is in producing the routines which generate the data and provide graphical output. The part of the program which does the engineering calculation is often just a small fraction of the total. The program produced by the researcher is not user-friendly, but it is capable of the form-finding and structural analysis of cable nets. The program is included as an appendix.

Lastly, physical modelling was carried out in two workshops. The first was at Buro Happold. The second was undertaken with a group of third year architectural students at the University of Plymouth. The aim of the workshops was to explore model-making techniques in conjunction with the understanding and application of the principles

governing the design of lightweight structures. Photographs of both workshops are included in appendix 4.

The aim of this part of the work was to gain an insight into the culture of engineering practices operating in the field of unconventional practices, a difficult area for a conventional architect to comprehend.

PART III. THREE FURTHER BUILDING CASE STUDIES, FOUR FURTHER INTERVIEWS AND CONCLUSIONS.

Chapter 8. Re-examination of the research questions.

8.1. Reassessing the design process.

After the nine case studies and their analysis using the Grounded Theory, it was felt to be appropriate to further study the design process as an iterative and largely visual sequence of events. It was hoped that this would shed light on the differences between the design process of conventional and unconventional structures.

The interview questions and the analysis of the answers using the Grounded Theory were largely focused upon the development of designs after their initial conception. The reason for not concentrating upon the initial conception is not that this stage is not considered to be vitally important but that the conception stage is the most difficult to explore (Zeisel 1981).

There must be an explanation as to why designers never give the same solution to a design problem. As Alexander explains in his book 'Notes on the synthesis of form' the variation could be attributed to the fact that the relationship between a form and its context is not unique. That is because the designer's task is to create a form which fits within an ensemble of constraints. This can be achieved if the designer changes the definition of the problem or loosens the different constraints by stretching the form-context boundary (Alexander 1977).

The surprise at the plethora of design solutions to the same problem is associated with a deterministic view of the Universe which followed from the work of scientists and mathematicians such as Sir Isaac Newton. However, our current world view conditioned by quantum mechanics and more lately chaos theory would lead us to be more surprised if different designers produced similar solutions.

The explanation for multiple solutions could also be traced back to the association of other faculties to design. Design theorists have attempted to draw analogies not only between design and artificial intelligence or biological evolution but also linguistics, seeing them both as communication activities. The starting point is that each individual has a set of unique experiences in life. In order for the individual to communicate these experiences logic is necessary. According to Lyons (1982) the ostensive relationship between a symbol and what it symbolises breaks down when the communication of feelings and emotions takes place. The logic required is based on the relationship between things. In the same way senses are part of the same nervous system. Gestalt psychologists believe the theory that the activities of all senses such as vision are mental (Wertheimer (1938), Koehler (1938), Gordon (1989)). An expansion of this argument could be that cultural symbol systems are part of the central nervous system in the same way senses are. Therefore senses and cultural symbol systems will share the same organising structure.

As with verbal languages, in visual 'languages' individuals 'match the data from the flux of visual experience with image-cliches, with stereotypes of one kind or another, according to the way they have been taught to see' (Kepes 1969, p.8). These image-cliches and stereotypes or symbols comprising symbol systems which are retained as abstract visual models that individuals store as their mental stock. These symbol systems, although structured both as a whole and at an individual level, allow new ideas to be introduced. These ideas will remain new up to the point where communicators initiate them and the initial ideas will be transformed while the emerging one will acquire a common usage.

When the above discussion refers to design we have to bear in mind that, despite the similarities of verbal language and visual language, thinking and communication are not as close in verbal language as in design (Brawne 1992).

The design process is a creative problem-solving task in which the solution of the original problem creates further problems to solve. The initial attempts at the resolution

of the problem start from the same place for each individual designer irrespective of his or her talent and imagination. The variability of possible ways of resolving a problem could also be attributed to the different experience and knowledge individuals possess. Seeing and imagining are the most significant activities the designer will employ in order to produce form. Bevin has talked about seeing as a personal experience influenced by thought processes, memory and associations which lead to widely differing interpretations of any given subject. Imagery can be perceptual or conceptual. The former relates to real things whereas the latter derives from emotion, fantasy and invention (Bevin 1984).

During the design process the problem-solver will utilize experience and knowledge in order to pin down a possible solution to the problem. This is when the abstract visual models become available. These visual models have then to be translated to built form. However, this solution is likely to contain new difficulties which will require reassessment and alterations to the found solution. Backtracking is not only unavoidable but essential to the improvement and quality of design (Amarel, 1968; Asimow 1962; Guena 1969, Zeisel 1981). The problem-solver will have to use knowledge in order to eliminate this difficulty while following the same problem-solving cyclic process. The new solution will have similar and new difficulties which will have to be resolved. Information will eventually produce a critical transition. The use of this information will lead to a novel solution if the problem solver pushes it in a new direction. What is certain is that no novel solution comes out of the blue but it evolves from earlier attempts (Weisberg 1986).

But how does one abandon an idea to attempt another one? As Magee (1973) describes in his book, Popper discussed the rigorous testing a theory has to undergo in order for it to be abandoned or carried forward. In the case of sciences this testing has to survive confrontation to a much greater extent than in the arts. However, we cannot assume that the sciences are not as creative as a work of art. This can be justified by looking at famous scientific discoveries. Such discoveries require a leap of the imagination

starting from existing knowledge. The bigger the leap the bolder the theory produced. Magee has argued that every discovery contains 'an irrational element' or 'a creative intuition'. Thus although theories are put forward and judged on the basis of evaluation of past performance 'falsifiability is the criterion of demarcation between science and non- science' (ibid, p. 43).

Alexander (1977) has reinforced the importance of intuition in creation and has then associated it with invention. Characteristically he stresses the danger of confusion between intuition and the possibility of asking reasonable questions in a systematic process such as design. Architectural decisions can be safely backed up by resurrected styles. This issue has caused a long debate on the credit given to architects and engineers when it comes to the organisation of the physical world. Hence, it has been argued that a less talented engineer is more reliable than designers who "hide their gift in irresponsible pretension to genius" (Alexander 1977, p. 11). No matter who is responsible for the creation of the physical world or the creation of form as the outcome of a design problem there is 'no general symbolic way of generating new alternatives. Or rather those alternatives which we can generate by varying existing types do not exhibit the radically new organisation that solutions to new design problems demand. These can only be created by invention' (ibid, p.74).

There are certain similarities between a scientist and an artist in the pursuit of his or her aims. As Norberg-Schulz (1985) has explained 'whether we employ gestures, other kinds of actions, images or sounds, these have to be ordered and connected with a system of expectations to be meaningful'. This, Cherry (1957) believes to be the common denominator between science and art. Bevin has explained that orderly processes based on mathematics determine the results of scientific and engineering problems. Although art is considered to be more intuitive, the process of design follows similar orderly procedures to those used in science. The point is that in both cases 'the development of the solution is fundamentally a matter of problem-solving (Bevin 1984, p. 24). Hence, in order to bring into being a conceptual scheme,

scientists and artists 'are both trying to extend our understanding of experience by the use of creative imagination subjected to critical control, and so both are using irrational as well as rational faculties: Both are exploring the unknown and trying to articulate the search and its findings. Both are seekers after truth who make indispensable use of intuition' (Magee 68).

8.2. Case studies.

The nine case studies gave ambiguous clues as to what are the differences between the design process of conventional and unconventional structures or as to the further difficulties of the design process of unconventional structures. These were the two research questions first posed in chapter 1. For the external validation of the research three further case studies were chosen which were unconventional according to the definition given at the beginning of the thesis. Since no interviews were used for these case studies, there is no need to preserve the anonymity of the design teams. The three case studies were deliberately chosen to be not tension structures and one of them is not a roof structure.

The further case studies are:

1. The Stadelhofen Railway Station in Zurich, Switzerland by S. Calatrava in 1982.
2. The Pavilion of the Future, Expo '92, in Seville, by Martorell-Bohigas-Mackay and Peter Rice, and
3. The Channel Tunnel Railway Terminal at Waterloo, London 1993, by N. Grimshaw and Partners and T. Hunt.

8.2.1. The Stadelhofen Railway Station in Zurich, Switzerland (1982).

Designer: S. Calatrava.



fig. 25. The Stadelhofen Railway Station in Zurich, Switzerland. Source: *The New Spanish Architecture*, p.99.

The building is the outcome of a winning scheme submitted for a competition by Calatrava in association with Arnold Amsler and Werner Rueger (Frampton 1989). The scheme has been praised not only for its structural ingenuity but also for its urban adaptation. It is a 270m long curve which follows the line of a hill to which it is attached. It has a three level cross section which remains identical across its length (Sharp 1992). The design is a glorification of the tripartite Y-shaped column which carries the steel and glass canopy over the original platform and also covers the inclined pergolas on the upper promenade. References to a dinosaur's tail have been made about the enormous concrete rib cage.

History.

Often in the work of Calatrava structures are recognised as the transformation from moment diagrams to building forms. In the case of the Stadelhofen Station Calatrava is trying to exemplify the concept of torsion, since tension and compression have a simple linearity (A+U, 1986). Nicolini (1989) draws parallels between Calatrava's intervention in Stadelhofen and Piranesian pedestrian undercrofts. This parallel derives from the dramatic manner in which the station is side-lit. Also it is worth noting the amalgamation of materials and forms which makes the Station one of the most complex projects Calatrava had designed up until that time (ibid).

Calatrava himself has said that Stadelhofen is a collection of bridges (Tischhauser 1992). There is no association between the concept for the Station and 19th century stations. Calatrava elucidates the transdisciplinary in his work by exploring in parallel the structural character and the enhancement of the existing undeveloped antiplace.

Tischhauser (1992) has described the Stadelhofen promenade as a hand, the three fingers of which hold the glass canopy. But what matters to Calatrava is not the form of the three fingers but the equilibrium which he best observes in the human body. Although there have been long discussions on the associations of Calatrava's ideas with the organic, his descriptions do not allow him to be pinned down. "The skeleton of an animal is not a treasury of form, it serves only to clarify the correctness of its parts, finally assisting in the stability of movement. The skeleton is similarly recognisable in the gothic constructions where the envelope encloses completely, while the skin allows the bones to shine through. It has nothing to do with the form of bones." (Klein 1992, p. 22).

Tischhauser (1992) has talked about Calatrava's special ability to understand, visualise and use curves. However, he elaborates, saying that this aesthetic feeling is the outcome of nurtured sketching and endless 'rehearsal'. Calatrava talks extensively about his inspirations which however are scrutinised against previously conceived

phenomena. “The impression is not necessarily the development of an idea to build, but the building of an idea while unfolding creative power” (ibid, p. 29). Calatrava admits that Nature is a powerful stimulus in his creative process. Sharp (1992) however sees him in line with the interpretative approach of Antoni Gaudí rather than Guimard, Van de Velde or Horta whose interests lie more in the decorative use of the forms and structures observed in Nature. Calatrava has himself talked about the influence that Robert Maillart and Felix Candella have on the way he thinks.

Calatrava works mostly with sketches and shop drawings at the beginning of the process and then produces scale models before he finalises the form (Sharp 1992). Unlike other architects in Switzerland or elsewhere he uses computers largely for calculation purposes. He strongly believes that the ability to draw is more than enough to translate ideas into a new reality. Computers can be used at the production, specification, development, managerial and statical stage and much less at the ‘formative creative edge’. Model making has allowed Calatrava to explore the movability of structural forms and therefore fulfil his special interest in kinetics (Nicolin 1989).

The above discussion does not enable us to state whether the Station roof is either unconventional or innovative. The two words unconventional and innovative are not interchangeable since an unconventional structure may not be innovative and a structure may be innovative even though it uses conventional construction techniques.

In this thesis we have focused upon the differences between the design processes of conventional and unconventional structures and in particular upon the problematic nature of the design process of unconventional structures. Calatrava has evolved a way of working which has produced a series of highly individual buildings and structures and in so doing he has been able to overcome the problematic nature of the design process of unconventional structures. Inasmuch as Calatrava’s work has a certain

consistency of form and influence, one might say that the station roof is 'conventional Calatrava'.

8.2.2. The Pavilion of the Future, Expo '92, in Seville, 1992.

Designers: Martorell-Bohigas-Mackay and Peter Rice.



fig. 26. The Pavilion of the Future, Expo '92, in Seville, 1992. Source: Peter Rice: *An Engineer Imagines*, p. 118.

The building is essentially a stone facade which supports the roof over the pavilion halls. The overall length is roughly 250m. It consists of 11 similar stone arches and 12 stone and steel towers to create a tall arcade structure from which the roof of the pavilion hall is suspended. "The ends of the roof beams projecting beneath the stone facade are suspended in pairs by hangers beneath each of the arches which rise to approximately 37m above ground level at their crowns" (Lenczner 1994, p. 172). The facade has its own stability independent of the building. Horizontal stability against wind loads is provided by a triangulated steel lattice system which works in collaboration with the stone columns. This spatial lattice structure links pairs of stone columns at 5m intervals 'to form a composite triangulated vertical tower which cantilevers from the ground' (ibid, p. 173). A set of equal radial forces at equal angular intervals loads the semicircular stone arch to support the roof beams below the arches.

History.

Lenczner (1994) explains in the introduction of his paper on the pavilion that the intention was to 'bring an ancient building material into the future'. This intention followed the interest of Peter Rice, the engineer of the design team to materialise an idea that had impressed him in the past. Rice (1992) explained that on a visit to Lisbon he noticed that in the Palazzo da Ajuda one of the facade walls was a free standing loadbearing wall, part of an uncompleted quadrangle. The astonishment caused by the efficiency of the wall in standing up impressed Rice who ever since had looked for the chance to materialise the same idea in a new building. When the commission for the Pavilion of the Future was allocated, the idea was put forward by Rice and was welcomed by the architects. In effect the concept of the free standing loadbearing wall became the starting point for the architecture of the Pavilion of the Future.

Rice (ibid) has described the creative part of the design process as a recollection of precedent buildings, the materials used and the construction or structural details invented for each case. Hence, knowledge of material properties together with past experience of the structural use of glass were crucial to the design. Structurally stone and glass have similar properties; they are brittle and they can carry compression much more efficiently than tension under which they both crack. The idea of using the same principles employed in the La Villete glass conservatories was expensive compared to the available budget. The main issue was to protect the stone from tension forces and sudden loads. The design team and builders worked to very tight tolerances and high levels of accuracy.

The form of the facade, derived from the notion of an aqueduct. In order to produce stone prefabricated elements the team based their decisions on past experience of precast concrete units. The arch units followed the same principles and were assembled with mortar joints.

The analysis method was developed from the behaviour of stone arches. Rice explained that the team studied ‘the theory of the way in which stone arch bridges worked, notably following the methods developed by Prof. Jaques Heyman at Cambridge University’ (ibid p. 122). The computer program tested a full range of loading conditions of earthquake and wind. The same method had been used by the same engineering practice, Ove Arup, on non-linear structures such as nets and fabric structures.

Peter Rice emphasises the association of innovation with existing ideas, ‘Innovation here was the development of existing ideas and the belief that they were relevant and applicable in the structure we were exploring’ (ibid, p. 123). Rice also stated that the Seville project, ‘demonstrates that there is nothing mysterious in the process of innovation. What is needed is just courage, care and attention to detail, and above all belief in getting started’ (ibid, p. 126). This is no doubt true, but most of us find it difficult to combine courage, attention to detail and belief.

David Mackey (1992) has written a personal tribute to Peter Rice. Engineers who find it difficult to draw may take heart from Mackey’s reference to Rice’s ‘awful Biro drawings’ (ibid, p. 168).

8.2.3. The Channel Tunnel Railway Terminal at Waterloo, London (1993).

Architects: N. Grimshaw and Partners

Engineer: T. Hunt.



fig. 27. The Channel Tunnel Railway Terminal at Waterloo, London (1993). Source: Structure, Space and Skin: The work of N. Grimshaw and Partners, p. 26.

The Terminal is the outcome of a closed competition. The roof structure is a series of two pinned asymmetrical trussed arches of a span which varies between 35 and 50m. The roof is 400m long and the station can handle 1500 passengers in four minutes. There is an inversion of tension and compression, hence between skin and structure, as the structure moves from east to west. Truss members are formed from telescopic circular sections.

History.

The team has claimed that the roof structure is reminiscent of Victorian train sheds. The asymmetry is determined by the site and the brief which required five train tracks. Thus the single track on the western side of the building means that the structure has to rise more steeply in order to clear the trains.

The irregularities of the site created difficulties in resolving the cladding of the roof. The one-off panel solution was rejected as extremely expensive and time-consuming. Grimshaw recollected memories of the structure of reptiles, tiled roofs and the articulation of train carriages to arrive at the final solution. Eventually, rectangular sheets, overlapping at the top and bottom, sheets were used with to handle flex and expansion by concertina-shaped neoprene gaskets.

Construction and structural details which Grimshaw had used in previous projects acted as and contributed to the resolution of the stainless steel castings. More specifically, similar castings were designed for the Financial Times Print Works and the Western Morning News and have since become Grimshaw's trademark.

Colin Amery (1988) has drawn parallels between Greek architects and Victorian engineers and Grimshaw's work in the way they use materials. Amery also stresses the similarities of Paxton, Prouve and Grimshaw in the evocation of structural roots.

Grimshaw has talked about the great influence that Buckminster Fuller, Paxton, Brunel and Prouve have had on his work. The recent projects of his practice are themes developed from his earlier work (Powel 1988). Grimshaw characterises his architecture as a balance between structural engineering and art. That is not only attributed to the influence that certain engineers or architects have had on his work but also to his education which started with his studying and almost qualifying as an engineer. He admires Aalto's way of thinking and similarly defends the role of the imagination.

8.2.4. Discussion.

All three projects can be considered unconventional according to the definition given at the beginning of the thesis and the designers of all three projects have been involved in the design of other innovative buildings.

The findings of this phase of the research indicate that the designers do not see the design process of innovative buildings as different from or more difficult than that of less innovative ones. The design process is seen as an iterative problem-solving task which employs preconceived visual models the designers have as mental stock. These models vary according to individuals' perceptions, their unique experiences and their educational background.

All three examples and their respective designers go beyond the barriers which have erroneously been established between architecture and engineering, or between innovation and conventionality.

Thus, although Calatrava sees the design process of innovative buildings as no different from the design process of less innovative buildings and the techniques he uses as being no different from the ones a 'traditional' designer would employ, he is one of the very few skillful designers who is both a talented architect and a creative engineer.

On the other hand Martorell-Bohigas-Mackay, the architects for the Pavilion of the Future admitted they would not have gone for anything as innovative without Peter Rice's participation. Peter Rice was a unique personality with great sensitivity in architecture, an engineer who would start considering any design problem by looking at precedent buildings or other artistic aspirations.

Lastly, Grimshaw is an architect with an engineering background. His heroes are mostly engineers and his approach to design is based on the exploration and evolution of structural or construction ideas he has employed in his buildings in the past.

We must bear in mind that all three designers are atypical. Calatrava, Rice and Grimshaw demonstrate the close relationship that is possible between architecture and engineering. This raises the question of whether it is reasonable to expect less gifted designers to have the skills of an architect and an engineer.

The method of assessing the design process by examining published works may be flawed since bad feeling between designers, mistakes and misunderstandings, are unlikely to surface.

8.3. Interviews with leading practitioners.

The final phase of the research consists of interviews with leading practitioners, two architects, Birkin Haward and Robin Snell, and two engineers, Sam Price and Mark Whitby. The aim of the interviews was to further examine issues raised in the nine building case studies.

The anonymity of these interviewees is not preserved since the questions they were asked did not refer to specific projects and therefore specific personalities. All four interviewees were asked the following questions:

1. Do you think that the dual architectural and engineering nature of unconventional structures influences the design process?
2. Do you think that the architectural language of unconventional forms is different from that for conventional ones and that this influences the process?
3. Is there a stronger interrelation and interdependence of architectural and engineering considerations when unconventional structures are designed?
4. Is there a necessity for simultaneous and equal involvement of architects and engineers from day one for unconventional structures? Is this more necessary than for conventional structures?

5. Is the lack of specific knowledge of technical and other issues a further difficulty of the design process of unconventional structures?
6. Does the degree of experience of individuals play an important role in the evolution of the process?
7. How does the different degree of familiarity that individuals have with means of communication and simulation affect the process?
8. Is it important that construction details and choice of materials are resolved at an early stage?
9. How significant is it for the process to learn from other people's mistakes and previous experience?
10. Are commitment, determination and enthusiasm necessary for innovation?
11. Which comes first, unconventional structures requiring close collaboration between engineers and architects, or close cooperation between engineers and architects producing unconventional structures?
12. Do you think that current educational practice equips architects and engineers to work together?
13. Is the borderline between the skills and roles of architects and those of engineers appropriate for the design of unconventional structures?

The interviews were tape recorded and the transcripts are given in appendix 7. The transcripts are annotated and the paragraphs numbered to facilitate their analysis.

The interviewees were chosen on the basis that they all have significant experience of both conventional and unconventional structures. All four of them have also been involved in teaching. The interviews were not analysed using Grounded Theory because the Grounded Theory is aimed at analysing data from a relatively large number

of semi-structured interviews. The specific questions in the final four interviews were themselves based upon issues which arose out of analysis of the eighteen case study interviews using Grounded Theory.

8.3.1. Analysis of the responses.

Question 1: Do you think that the dual architectural and engineering nature of unconventional structures influences the design process?

Even though there is no simple and clear definition of what is meant by unconventional structures, the interviewees recognised that the term had some meaning for them. In section 1.5 of this thesis it was stated that ‘the unconventional structures that will be examined in this study are long span structures covering column free spaces without employing beam-column structural systems’. In choosing these words the author was aware that there are unconventional structures with short spans, just as there are long spans which are conventional. However, it is understandable that the terms ‘unconventional’ and long span can sometimes be confused. “In a way theoretically, you can have unconventional with something very small can’t you? There isn’t long spans. It could just be a house or a detail, and you recognise that” (B. Haward, § 24).

There was agreement among the interviewees that at a fundamental level the design process of unconventional and conventional structures is the same. R. Snell stated that “the starting point is always the brief” (§ 20) and “in the design process one can use the same design philosophy whether one is designing a table or a chair or a house. It depends on the approach of a particular designer.” (§20). B. Haward described the cyclic nature of the design and testing of the cladding panels of the Sainsbury Centre. The cyclic nature of design has been related to Karl Popper’s analysis of the scientific method (Brawne, 1992). The cyclic nature of the design process may be even more apparent for unconventional structures since different parts of each cycle might involve specialists and physical testing.

Taking the interviews as a whole, the two engineers (Sam Price and Mark Whitby) seemed to have a stronger feeling than the two architects (Birkin Haward and Robin Snell) that the nature of unconventional structures influences the process. S. Price emphasised (§45) that engineers have to be able to give quick answers to architects' questions for the dialogue to continue and that they rely on experience to do this. By definition a structure cannot be unconventional if you already have experience of it.

Question 2: Do you think that the architectural language of unconventional forms is different from that for conventional ones and that this influences the process?

The answers to this question were not well defined. This is probably due to the lack of definition in the question itself and the fact that the language of form relies upon precedents which it is difficult to apply to a structure which is essentially unconventional. The answers were also related to the degree of familiarity individuals have with unconventional structures. B.Haward said "I don't know quite where you draw the line. I think for me it is just structure" (§ 11). R. Snell explained that "the architectural language is about more dramatic structures and that is by virtue of the fact that one is doing a more dramatic thing in that one is spanning a much larger space with less structure and this is going to be more exceptional" (§ 18). M.Whitby pointed out that "if anything the architectural form is a hindrance to the idea of making unconventional structure because it is a preconception in its own right" (§ 17).

Question 3: Is there a stronger interrelation and interdependence of architectural and engineering considerations when unconventional structures are designed?

Question 4: Is there a necessity for simultaneous and equal involvement of architects and engineers from day one for unconventional structures? Is this more necessary than for conventional structures?

The interviewees made statements relevant to these two questions simultaneously. Technical issues are just as important in designing a conventional structure as an

unconventional structure, although the use of experience means that they are not constantly at the forefront of the designers' consciousness. S. Price said "So I don't think that unconventional necessarily means big spans. But I think it would be true to say that totally conventional construction does not need the same degree of close work involvement, between the architects and engineers as unconventional" (§1). In using simple rules based on experience the architect is acting as his or her own engineer.

In the case of unconventional structures, more specialised expertise is required: "I think I am saying that in all circumstances I think it would be better if the architect and the engineer work close together, because I suppose there is more of a risk...." (S. Price, §9). The other engineer, M. Whitby, said that "very good architects are people who start with blank pieces of paper when they are having conversations and things grow out of those pieces of paper. Other architects have all their ideas in advance." (§23).

These and other statements made by the interviewees are evidence that the answers to question 3 and 4 are both 'yes'.

Question 5: Is the lack of specific knowledge of technical and other issues a further difficulty of the design process of unconventional structures?

Question 6: Does the degree of experience of individuals play an important role in the evolution of the process?

These two questions are also linked. All four interviewees answered 'yes' to question 5. This supports the hypothesis that the design of unconventional structures is more difficult than that of conventional structures. S. Price qualified his response by going on to say that "lack of specific knowledge may be a difficulty in the design of quite conventional structures too. If you just don't happen to have the right knowledge." (§37). They also answered 'yes' to question 6 and M. Whitby made the very interesting point that "people who pioneer ideas are less likely to get caught out by them than the

people who follow along behind. Because they are always thinking about them,.....look easy but they might be very difficult.” (§42).

Question 7: How does the different degree of experience that individuals have with means of communication and simulation affect the process?

This question was aimed at eliciting the problems caused by the inadequacy of two-dimensional drawings and sketches in the design of complex three-dimensional forms. The skills and expertise in the construction of physical and computer models lie with a small number of specialists, mainly engineers. B. Haward said that he had learnt the use of models when working at Fosters on unconventional buildings and that he now uses models in the design of conventional buildings. M. Whitby explained that “you need to do it less for a straightforward building than you do on an unconventional one” (§ 54). Experience is an aid in most things one does. It is, however, difficult for those who have gained this experience through practice to understand the problems of a newcomer in the field. The case is similar to that of a native speaker of a language who is often ignorant about the rules that govern his or her language, but even so he or she speaks it fluently and accurately.

However, experience can be a hindrance. R. Snell said that “if you are an expert technician, who knows all the technology, that can actually bring with it inhibitions that if one doesn’t have that knowledge one is slightly freer with” (§ 39).

This is a very interesting observation; speaking to engineers it is clear that they can find architects’ lack of technical expertise both exasperating and a source of innovation and inspiration.

Question 8: Is it important that construction details and choice of materials are resolved at an early stage?

All interviewees recognised the importance of construction details and choice of materials. B. Haward stated that he felt that it was important to be studying a number of

alternative details and materials which were resolved as the design progressed. S. Price said that “in almost any building, however conventional or unconventional, it is important that the choice of materials and construction details are there” (§ 72). M. Whitby explained that ‘it is no good suggesting something that can’t be realised’ (§ 57).

Question 9: How significant is it for the process to learn from other people’s mistakes and previous experience?

All interviewees emphasised the importance of learning from other people’s mistakes and previous experience. R. Snell quoted Peter Rice saying at a meeting that it is important to learn from your mistakes. B. Haward made the point that “you clearly want to try and use experts who have been there before, if you can.” (§ 7).

Professions gather together the lessons learnt from mistakes and experience in guides and standards. One of the difficulties experienced in the design of unconventional structures is that such publications often do not exist. Then it is experience of the fundamental process itself that is paramount.

Question 10: Are commitment, determination and enthusiasm necessary for innovation?

All agreed emphatically. R. Snell added rigour as one of the qualities necessary for innovation. M. Whitby said “You can’t have an idea and not want to follow it through. You have to be determined because there are plenty of people in life who will tell you it’s not worth doing and enthusiasm yes, because you have to get other people to believe in the idea in the first place...” (§70). B. Haward explained that commitment, determination and enthusiasm are necessary in the case of innovation “if you are trying to do something that hasn’t been done before, it is going to involve a lot more time and effort and worry. If you want a quite life you don’t try and innovate.” (§ 67).

Question 11: Which comes first unconventional structures requiring close collaboration between engineers and architects, or close cooperation between engineers and architects producing unconventional structures?

Answers to this question were not clear. Perhaps this is not surprising since it concerns events which take place as or even before the design process starts. Architects and engineers may find themselves working together on a competition or a client may approach them because he or she likes their previous work. S. Price emphasised at this point the preconceived visual models a designer has before he or she joins a team. “The first part suggests that you only get a thoroughly unconventional structure because of close cooperation and I don’t think that can be right, can it? I don’t know how well did Peter Rice know the Spanish architect to build that mad wall.” (§ 97).

Question 12: Do you think that current educational practice equips architects and engineers to work together?

The answers to this question were interesting. Rather than paraphrase their answers, the following are quotes from the transcript:

“I don’t really know the answer to that, I think it is probably getting better...My feeling is that an awful lot of practices are quite comfortable working with engineers right from the beginning. That is my gut feeling, because otherwise you wouldn’t get the sort of results that you do get now. There is a tremendous compatibility....all those middle generation practices must do it in order to get the thing looking right in the end. You can’t do it any other way, you have to sit down and do it together. So, I think quite a lot of students who haven’t had the experience at school, because it is quite difficult to simulate it, find out pretty quickly in practice” (B. Haward, §128).

“Well, I think education should equip people to work together, whether it be engineers or architects or quantity surveyors and I think one just has to get on with people involved and to have a good working relationship with them. Whether it be an architect or a builder -I think it is just as important to get on and work together with the people who are actually making the products. But does education serve this? What to educate in social sciences, managing skills? No, I don’t think it does actually. Probably in a school of architecture one doesn’t learn about these things. The only way one learns is

by actually doing it. You only get that by actually working. You only start to understand relationships between designing people by actually doing the job and then it comes down to personalities. I am not sure you can actually teach it. You can make people aware of the process but until you do it, I don't think you really understand it" (R. Snell, §63-65).

"Absolutely not. I think that architects are fairly badly educated in quite a lot of respects and engineers are appallingly educated, really very badly educated.....In quite a lot of schools of engineering in the country, design is not taught at all, it doesn't even come into anyone's head. It's analysis -and you certainly have to be very good at analysis, but the whole function, the purpose of analysis is to analyse something that you have invented to design and most of the people who teach engineering know nothing about design. They just don't know how it's done or what really counts, or what the process is like and it is a very difficult process...Totally different . If we were trying to equip architects and engineers to work closely together we would also attack the very considerable cultural differences between architects and engineers." (S. Price, §113).

"The best education an engineer can have is to become proud of himself being an engineer. That is all they need to be, they need to have courage in their own ability and then their professional standing. They have to know that what they have to sell is something of value and that is fine if you can do that. The architects are taught in many respects how to be confident, presentational skills, etc. Confidence in engineering means they are blind to the weaknesses. I am all the time saying you cannot be confident, if you think you have done it, go away and look again. It is very, very dangerous to be confident in engineering. You have to be able to adopt the approach of challenging yourself and being challenged by others, it is very dangerous, you know confidence is a front, a weakness sometimes" (M. Whitby, §100-102).

The above four quotes are not contradictory. They emphasize confidence, personal skills, rigour and learning "on the job".

Question 13: Is the borderline between the skills and roles of architects and those of engineers appropriate for the design of unconventional structures?

The answers to this question were disparate. B. Haward said: “Not particularly I think good architects are also engineers and good engineers are also good architects.I think the best people move across boundaries” (§133).

In his lecturing and writing M. Whitby emphasises the importance of engineering culture in its own right, steam locomotives, aeroplanes, bridges and so on. This is healthy since engineers and architects can best work together if each is comfortable with his or her part of a larger culture. In speaking to many engineers and architects the consensus would seem to be that engineers should be encouraged to develop some of the skills of architects and vice versa, but that fundamentally engineers and architects come from different cultures and each should respect the other for that.

8.3.2. Discussion.

If one looks at the comments that the four interviewees gave to the thirteen questions as a whole, it can be seen that they do not support the hypothesis that the design process of unconventional structures is different from that of conventional structures. For both types of structure design consists of a cyclic process in which solutions are put forward, tested and accepted or rejected.

However, the answers did support the second hypothesis, that the design process of unconventional structures is more difficult than that of conventional structures. This difficulty is largely related to technical issues although there are also the problems of the architectural language of form and the lack of precedents.

Nobody will dispute that architects and engineers should work closely together from the very beginning, that they should display enthusiasm and commitment, or that they should choose materials and details early in the design process. In ‘conventional’ practice they find ways around such good practice -that is what the ‘conventional’ is

for, so that the assumptions can be made. In ‘unconventional’ design we see ‘best practice’ no assumptions can be made, everything has to be thought out anew.

Chapter 9. Overview and conclusions.

9.1. Overview

This thesis studies the design process of unconventional structures starting with the hypotheses that it is different from and more difficult than that of conventional structures.

The work to investigate the validity or otherwise of these hypotheses comprised four main parts:

1. A study of the technical difficulties associated with long-span roof structures.

The prime aim of this part of the work was to familiarise the author with the problems associated with a particular class of unconventional structures and the ways in which architects and engineers have overcome them.

2. Nine case studies of unconventional structures:

1. Sydney Opera House (1957-1973).
2. The Institute of Lightweight Structures in Stuttgart, (1968).
3. The Munich Olympic Roofs, Germany (1972).
4. The Mannheim Garden Centre, Germany (1975).
5. The Munich Aviary, Germany (1975-1980).
6. The King Abdul Aziz University Sports Hall in Jeddah, Saudi Arabia (1979).
7. The Diplomatic Club in Riyadh, Saudi Arabia (1980).
8. The Olympic Ice Stadium in Calgary, Canada (1981).

9. The Schlumberger Research Centre in Cambridge, U. K. (1985).

These structures are predominantly long-span roof structures, but are made of a variety of materials that included concrete, steel cables, fabric and timber. The buildings were chosen to include a reasonably wide range of unconventional structures without being so dissimilar as to make comparison impossible.

The buildings were investigated primarily by interviewing one architect and one engineer who had worked on the project, except for the first two pilot studies in which an architect was interviewed for one and an engineer for the other. Thus the choice of the projects was influenced by the fact that the designers had to be alive and living in Europe. An extremely eminent architect and an equally eminent engineer, both of whom had been involved with a number, but not all, of the projects were also interviewed. Anonymity of these eighteen interviewees and also of the people they discussed is preserved in the thesis. This is because many of the comments that were made about other individuals were of a critical nature.

3. A literature review of three further unconventional structures:

1. The Stadelhofen Railway Station in Zurich, Switzerland(1982).
2. The Pavilion of the Future, Expo '92, Seville, Spain (1992).
3. The Channel Tunnel Railway Terminal at Waterloo, London, U.K. (1993).

The designers of these structures were different from those of the first nine case studies.

4. Interviews with two architects and two engineers who have experience with both conventional and unconventional structures. They were:

1. Birkin Haward from Van Heyningen and Haward.
2. Robin Snell from Snell Associates.

3. Sam Price from Price and Myers Engineers.

4. Mark Whitby from Whitby and Bird Engineers.

The anonymity of these interviewees is not preserved since the questions which they were asked were of a more general nature and reference to personalities was largely avoided. These final interviewees were not involved in any of the previous case studies, except Robin Snell who did work on the Schlumberger project.

9.2. Answering the research questions.

This study started with two research questions:

Research question 1: What are the differences between the design process of unconventional structures and the design process of conventional structures? To what are these differences attributed?

Research question 2: What are the difficulties that make the design process of unconventional structures more problematic than the design process of conventional structures? To what are these difficulties attributed?

The conclusions drawn at the end of the first nine case studies are as follows:

The design process of unconventional structures has a distinctive character. More specifically, it was found that architectural and engineering considerations are interrelated and interdependent because the form and the structure coincide. One of the consequences of this is the change imposed on the organisation of the design team. The norm that requires the architect to come up with a form and the engineer to follow with suggestions of a suitable structure does not apply. Architects and engineers must work together from the very beginning, and make all decisions together and simultaneously.

Differences between the design processes of conventional and unconventional structures due to the dual architectural and engineering nature of unconventional structures were identified. Important points to emerge were:

- i) the architectural language of forms.
- ii) the strong interrelation and interdependence of architectural and engineering considerations,
- iii) the simultaneous and equal involvement of architects and engineers from day one,
- iv) the specific knowledge of technical and other issues,
- v) the degree of experience of individuals,
- vi) the different degree of familiarity that individuals have with means of communication and simulation,
- vii) the importance of the early resolution of construction details and choice of materials,
- viii) the importance and benefits of learning from other people's mistakes and previous experience, and
- ix) the commitment, determination and enthusiasm necessary for innovation.

However, that many of the conclusions also apply to conventional structures and therefore, for these conclusions to be valid answers to the research questions, it is necessary to find some means of further comparing conventional and unconventional structures.

This led to the three further case studies, the Stadelhofen Railway Station in Zurich (1982), the Pavilion of the Future, Expo '92, Seville (1992) and the Channel Tunnel Railway Terminal at Waterloo, London (1993). These were studied via a review of the

literature. It is difficult to form conclusions from the literature review of the three case studies since the articles and books were not written specifically to answer the research questions. In particular published material tends to emphasise the designers' success in solving problems rather than how difficult they found it.

The interviews with Birkin Haward, Robin Snell, Sam Price and Mark Whitby were more fruitful. Firstly they highlighted the imprecise nature of the term 'unconventional structure', although no better term emerged. All four interviewees recognised that design is a process which involves solving a number of interrelated problems, whether it be designing a chair, steam engine or building. Tentative solutions are put forward and tested against various criteria, further solutions are investigated and so on in a cyclic manner.

The engineers accepted that there was a real difference for them in designing unconventional structures. This was that it was not possible to rely on past experience to make a judgment as to whether a proposed solution was viable or not. Past experience can either be one's own or that of other engineers as laid down in standards, text books and research papers.

In simple terms one might say that design is about going around in circles, putting forward ideas, testing them and accepting or rejecting them. In architecture the tests are largely qualitative. In engineering they are more quantitative and **in designing an unconventional structure it is necessary to invent not only the solution but also the test.** This was so for the case study projects labelled P1, P3, P4, and P5.

Thus one can focus on the similarities between the design processes of conventional and unconventional structures. The ability to design and make objects and to have aesthetic sensibility are amongst the most fundamental human attributes. Whatever one is designing, the same brain functions must essentially be at work.

On the other hand the difficulties associated with taking risks and of interacting with other people when the rules of interaction are not clear, are also part of the human condition. In architecture and engineering there are many difficulties to overcome, aesthetic, planning, financial and technical. In addition, there is often pressure of time, in terms of both deadlines and the financial viability of the design office. All these problems may be compounded in the design of unconventional structures.

The human mind requires simple, clear models with which to construct thoughts. When we use words like “engineer” or “architect” we all have models in our minds. Society functions partly because we understand our roles relative to other people in terms of these simple models. As society changes and perhaps becomes more complex roles change. The interaction of computers and human thought also changes the way that we think and the skills that we need.

This research is interdisciplinary in that it considers architecture, engineering and also the way in which people behave and interact -the social sciences. The social sciences are very concerned with methodology, with good reason, given possible abuses. The methodology adopted in analysing the nine main building case studies is known as the Grounded Theory. The author found it a useful tool for classifying a large amount of qualitative data. However, the method is complex and it is difficult to strike a balance between rigourously following the methods dictated by the theory on the one hand, and the need for simplicity and brevity on the other. Despite problems with the methodology, the interviews with architects and engineers provided data which could not have been obtained in any other way. They form an important historical record.

9.3. Value of the work

The aims of a Ph.D. thesis are contribution to knowledge and the education of its author. In this thesis the contribution to knowledge is in the understanding of the design process of unconventional structures. This thesis is not primarily a technical

work and therefore its value is in modifying designers' general attitudes rather than the specific details of their work.

The research shows that the design process of unconventional structures follows much the same basic principles as that of conventional structures. This should encourage architects and engineers without experience of unconventional structures to consider an unconventional solution where they think it appropriate. The research also shows that unconventional structures cause additional pressures and difficulties for the design team. However, none of the interviewees expressed regret at having worked on unconventional structures -the satisfaction outweighs the problems.

Overall, the thesis has:

1. achieved the assembly of an extensive record of the design process of nine unconventional structures,
2. applied Grounded Theory to the analysis of the interviews, and
3. given an insight into the nature of the design process of conventional and unconventional structures.

The application of the Grounded Theory facilitated the classification of the voluminous data collected from the case study interviews. However it was only partially successful in that the complexity of the method tended to cloud the issues.

The Grounded Theory raised issues from the case study interviews which could only be investigated using ideas from design theory and the four further interviews with leading practitioners. The application of design theory and the four further interviews modified the relative weighting of the conclusions from the Grounded Theory.

Research based on interviews naturally tends to produce verbal rather than visual information. Even if interviewees have drawings and photographs to illustrate some

points, they are rarely to hand. Future work might ask interviewees to try and arrange some visual material before the interview.

9.4. Concluding Remarks.

There is something which can be labelled a design process, which has certain characteristics involving problem-solving with the intention of making some object in the real world.

The design process of conventional and unconventional structures is essentially the same, refuting the first hypothesis, but the design of unconventional structures involves a greater number of iterations to eradicate difficulties. In architecture tests are largely qualitative. In engineering they are more quantitative and when designing an unconventional structure it is necessary to invent not only the solution but also the test.

The design process of unconventional structures involves additional thought by and additional pressures upon the design team. More specifically, the necessity of the early involvement of engineers and the use of experts in areas such as form finding is crucially important.

Much has been said in this thesis about the problematic nature of the design process of unconventional structures. It would be unfortunate if this were to cloud the enthusiasm and determination that architects and engineers show in the design and construction of such structures. The satisfaction obtained in overcoming problems makes it all worthwhile. A large part of the satisfaction is obtained from working as part of a team with colleagues from other disciplines to produce a building no one person could have produced on their own. Joint work between architects and engineers is to the benefit of both disciplines and ultimately leads to an integrated engineering architecture. Architects working with engineers can materialise their ideas, and engineers working with architects find an opportunity to express their creativity at the first stages of conception.

If the work contained in the thesis is to be of any value, then it must change, perhaps to some small extent, the way in which designers work together. This could simply be by increasing awareness of the difficulties and possibilities in the design of unconventional structures. Every building, or structure, is unconventional in some way and, therefore, the lessons learnt from the study of the design process of very special buildings can also be applied to the most humble.

Engineering and architecture are separate disciplines which overlap in complex and ever-changing ways. There are perhaps no true engineer/architects, but there are engineers with a true understanding of the essence of architecture and architects with a true understanding of the essence of engineering. Certain elements of the design process, especially at its early stages are the same for both architects and engineers; they have both to be triggered off by an image. Perhaps this thesis will help engineers, architects and educators to develop a deeper relationship between engineering and architecture.

References

- Ackermann, K. (1991) *Building for Industry*. UK: Watermark Publications.
- Addis, B. (b, 1992) *The Art of Structural Engineering*. London: The Building Centre Trust.
- Addis, B. (c, 1992) *The Interaction of Structure and Services*. London: The Building Centre Trust.
- Ahm, P. (1970) 'Some thought on engineering design'. *Concrete*, January, 22-26.
- Akin, O. (1978) *How Do Architects Design. In Artificial Intelligence and Pattern recognition in Computer Aided Design*. Latombe, ed. IFIP, North Holland Publishing Company, 65-104.
- Alexander, C. (1977). *Notes on the Synthesis of Form*. Cambridge/Massachusetts/ London: Harvard University Press.
- Allsopp, B. (1988) 'An Olympic legacy'. *Canadian Architect*, February, 33, (2), 17-29.
- Amery, C. (1988). *N. Grimshaw and Partners, Book 2, Process*.
- Ansell, M., Barnes, M. and Williams, C. (1984) 'Structural properties tests for coated fabrics'. *The Design of Air-supported Structures*, Bristol: Churchill Hall, The Institution of Structural Engineers/ The Chartered Institution of Building Services/ The Chartered Institute of Building/ The University of Bath, 31-34.
- Archer, L. B. (1964) *Systematic Methods of Designers*. London: Council of Industrial Design HMSO.
- Architectural Forum, (1964) 'Nervi gives a factory the grace of a bridge'. July, 111-113.

Architecture and Urbanism, (1986) 'Santiago Calatrava', Sept. pp. 90-112.

Arup, O. (1966) 'Art and architecture, the architect: engineer relationship'. *RIBA Journal*, August, 350-359.

Arup, O. and Zunz, G. (1969) 'Sydney opera house'. *The Structural Engineer*, March, No 3. Vol. 47, 99-131.

Asimow, M. (1962) *Introduction to Design*, N. J.: Prentice Hall, Englewood Cliffs.

Bach, K., Burkhardt, B. and Otto, F. (1987) 'Forming bubbles'. *IL 18*, Stuttgart: IL.

Barnes, M. (1975) 'The applications of dynamic relaxation to the topological design analysis of cable, membrane and pneumatic structures', *2nd International Conference on the Space Structures*, University of Surrey, Guildford, September, 211-219.

Barnes, M. (1988) 'Formfinding and analysis of prestressed nets and membranes'. In: *Non-conventional Structures: Proceedings of the International Conference on the Design and Construction of Non-conventional Structures*, Vol. 1. May (B. H. V. Topping, eds), 327-337.

Barnes, M. (1992) 'Wind load validation of low rise air structures'. *Surface-stressed Building Structures*, International Association for Bridge and Structural Engineering, Henderson Colloquim, Pembroke College, Cambridge, 21-22 July.

Baron, R., Kerr, N. and Miller, N. (1992) *Group Process, Group Decision, Group Action*. G. Britain: Open University press.

Baume, M. (1967) *The Sydney Opera House Affair*. Sydney: Halstead Press.

Becker, H. (1968) 'Social observation and social case studies'. In D.L. Sills (ed), *International Encyclopedia of the Social Sciences*, Vol. 11, New York: Macmillan and Free Press.

Belbin, M. (1981) *Management Team. Why They Succeed or Fail*. G. Britain: Butterworth-Heinmann Ltd.

Belbin, M. (1993) *Team Roles at Work*. G. Britain: Butterworth-Heinmann Ltd.

Berendt, J. (1976) *The Jazz Book* Frogmore, St. Albans, Herts: Granada publishing Ltd.

Berger, H. (1985) 'The evolving vocabulary of fabric structures'. *Architectural Record*, March, 152-156.

Bevlin, M. (1984) *Design Through Discovery*. N. Y.: CBS College Publishing, Sixth Edition.

Billington, D. P. (1983) *The Tower and the Bridge. The New Art of Structural Engineer*, New York: Basic Books, Inc.

Bobrowski, I. (1985) 'Calgary's olympic saddledome'. *Space structures 1*, 13-26.

Boys, R. (1963) 'Under tension'. *Architectural Review*, vol.134, No.801, Nov., 325-334.

Brancatelli, D, (1984) 'Il 'Saddledome': stadio olimpico del ghiaccio a Calgary (Canada)'. *L'Industria Italiana del Cemento*. No 5, 280-313.

Brannon and Maynard Moody (1979) Applying the logic of sample surveys to qualitative case studies: The case cluster method. *Administrative Science Quarterly*, 24, 582-9.

Brawne, M. (1992) *From Idea to Building: Issues in Architecture*, Oxford: Butterworth Architecture-Heinmann Ltd.

Brenner, M. (1985) 'Intensive interviewing'. In M. Brenner, J. Brown and D. Canter (Ed.), *The Research Interview. Uses and Approaches*. Florida: Academic Press, 147-161.

Brenner, M., Brown, J., Canter, D. (1985) 'Introduction'. In M. Brenner, J. Brown and D. Canter (Ed.), *The Research Interview. Uses and Approaches*. Florida: Academic Press, 1-7.

Broadbent, G. (1973) *Design in Architecture. Architecture and the Human Sciences*. London: Wiley and Sons.

Bryman, A. (1989) *Research Methods and Organisational Studies. Contemporary Social Research: 20*. London: Unwin Hyman Ltd.

Buchholdt, H. A. (1985) *Introduction to Cable Roof Structures*. Cambridge: Cambridge University Press.

Burgelman, R. (1983) 'A process model of internal corporate venturing in the diversified major firm'. *Administrative Science Quarterly*, 28, 2, 223-244.

Calatrava, S. (1989). 'Dissertations'. *El Croquis: Monograph on Santiago Calatrava*. Madrid.

Canter, D and Kenny, C. (1982) Approaches to environmental evaluation: an introduction'. *International Review of Applied Psychology* (SAGE, London, and Beverly Hills, Vol. 31. In: *Group Dynamics. Research and theory*. London: Tavistock Publications, 69-94.

Cartwright, D. and Zander, A. (b, 1953) 'Individual motives and group goals'. In: *Group Dynamics. Research and theory*. London: Tavistock Publications, 345-369.

Cartwright, D. and Zander, A. (c, 1953) 'Origins of group dynamics'. In: *Group Dynamics. Research and theory*. London: Tavistock Publications, 3-32.

Cartwright, D. and Zander, A. (d, 1953) The structural properties of groups. In: *Group Dynamics. Research and theory*. London: Tavistock Publications, 641-668.

Cherry, C. (1957) *On Human Communication*; New York/London.)

Concrete, (1986) 'Bridging the gap between the discipline of architecture and engineering', April, 152-154.

Cook, M. (1992) 'Air-supported structures, response to wind load'. *Surface-stressed Building Structures*, International Association for Bridge and Structural Engineering, Henderson Colloquim, Pembroke College, Cambridge, 21-22 July.

Coomber, M. (1989) 'Tension to detail'. *Building*, 25 August, 48-50.

Coyne, R. D., Rosenman, M. A., Radford, A. D., Balachandran, M. and Gero, J. S. (1989) *Knowledge-based Design Systems*. Reading: MA, Addison-Wesley.

Croft, D. and Hooper, J. (1974) 'The Sydney opera house glass walls'. *The Structural Engineer*, June, No.6, Vol, 52, 216-220.

Cross, N. (1984) *Developments in Design Methodology*. U.K.: John Willey, Chichester.

Cross, N. (1986) 'The changing design process'. In Roy, R. and Wield, D. (Ed), *Product Design and Technological Innovation*. G. Britain: Open University Press, 36-46.

Dalland, T. (1984) 'Architectural design criteria'. *International Symposium on Architectural Fabric Structures. The Design Process*. Proceedings Vol. 1, Nov., Orlando, Florida. USA, 121-123.

Davis, C. (1988) *High Tech Architecture*. London: Thames and Hudson Ltd.

Day, A. (1965) 'An introduction to dynamic relaxation'. *The Engineer*.

Day, A. and Green M. (1984) 'People and fire in air-supported structures'. *The Design of Air-supported Structures*, Bristol: Churchill Hall, The Institution of Structural Engineers/The Chartered Institution of Building Services/ The Chartered Institute of Building/ The University of Bath, 206-212.

Detail, (1972) 'Buildings for the Munich Olympics', Special no. in German, fully illusd, no. 4, July/Aug.

Dickson, M. (1992) 'Structural concept'. In: *The Art of the Structural Engineer*, by B. Addis, London: The Building Centre Trust, 9.

Dijkstra, W., Van der Veen, L. and Van der Zowen, J. (1985) 'A field experiment on interviewer-respondent interaction'. In M. Brenner, J. Brown and D. Canter (Ed.), *The Research Interview. Uses and Approaches*. Florida: Academic Press, 37-63.

Dolmetsch, A. (1915) *The Interpretation of the Music of the XVII and XVIII Centuries: revealed by contemporary evidence*. Handbooks for Musicians series. London: Novello.

Drew, P. (1976) *Frei Otto. Form and Structure*. G. Britain: Crosby Lockwood Staples.

Dubois, M. (1987) '2 into 1'. *Architectural Review*, January, 33-36.

Ealey, T, Liddel, I., and Pugh, J. (1986) 'The design and construction of the diplomatic club, Riyadh'. In LSA 86: *Lightweight Structures in Architecture. The First International Conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 424-435.

Ealey, T., Liddell, I. and Pugh, J. (1986) 'The design and construction of the diplomatic club, Riyadh'. In LSA 86: *Lightweight Structures in Architecture. The First International Conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 424-435.

Eekhout, M. (1972) 'Frei Otto and the Munich Olympic Games. From the measuring experimental models to the computer determination of the pattern'. *Zodiac* 21, 13-83.

Eekhout, M. (1988) 'Inside outward structures or how to arrive at high-tech'. In: *Non-Conventional Structures, Proceedings of the International Conference on the Design and Construction of Non-conventional Structures*, Vol. 1. Edited B. H. V. Topping, Civil-comp Press.

Engel, H. (1981) *Structure Systems*. Stuttgart: Van Norstand Reinhold Company.

Ericson, K. A. and Simon, H. A. (1984) *Protocol Analysis: Verbal Reports as Data*. Cambridge: MIT Press, MA.

Etzioni, A. (1964) 'Modern Organisations'. Prentice Hall.

Fishlock, D. (1986). 'Can technological projects be controlled?'. In: Roy, R. and Weild, D. (ed), *Product Design and Technological Innovation: a Reader*. Milton Keynes: Open University Press, 144-150.

Fodor, E. M. (1978) 'Stimulated work climate as an influence of choice of leadership style'. In: *Personality and Social Psychology Bulletin*. 4, 111-114.

Frampton, K. (1989) Look no hands-Santiago Calatrava and the well-tempered reconstruction.in Santiago Calatrava: Engineering Architecture, Basel/Boston/Berlin: Birkhaeuser Verlag, pp. 15-26.

Fung, Y. C.(1945) An Introduction to Aeroelasticity. New York: Scientific American Library.

Geiger, D. H. (1986) 'Exhibition halls and sports stadia: recent works of Geiger Associates'. In LSA 86: *Lightweight Structures in Architecture. The First International Conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 371-383.

Gibson, J. E. (1988) 'Steel framed hyperbolic paraboloid structures'. In: *Non-conventional Structures: Proceedings of the International Conference on the Design and Construction of Non-conventional Structures*, Vol. 1. May (B. H. V. Topping, eds), 65-72.

Giedion, S. (1964) 'The Sydney opera house'. *Zodiac* 14, 37-57.

Glaser, B. (1978) *Theoretical Sensitivity*. California: The Sociology Press.

Glaser, B. and Strauss, A. (1967) *The Discovery of Grounded Theory*. Chicago: Aldine.

Glen, F. (1975) *An Introduction to Social Psychology*. London: Methuen and Co. Ltd.

Goldbaum, H. (1976) 'Ventilating system with heating and cooling in the Mannheim Mutlihalle'. In IL 13, 174-177.

Goldsmith, N. (1984) 'Organic modernism and its potential revival in the developments of tensile structures'. *International Symposium on Architectural Fabric Structures. The Design Process*. Proceedings Vol. 1, Nov., Orlando, Florida. USA, 151-156.

Goldstein, A. (1963) 'Civil engineering design and designers'. *The Engineer*, August 9, 219-221.

Gordon, I. (1989) *Theories of Visual Perception*. G.B: St. Edmundsbury Press, Bury St. Edmunds.

Gordon, J. E. (1988) *The Science of Structures and Materials*. New York: Scientific American Library.

Grimshaw, N. (1988) Autobiographical note, in N. Grimshaw and Partners, Book 2 Process.

Gruendig, L. and Bahndorf, J. (1986) 'Formfinding of a roof structure for a health spa'. In LSA 86: *Lightweight Structures in Architecture. The First International Conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 246-253.

Gruendig, L., Linkwitz, K., Bahndorf, J. and Stroebel, D. (1988) 'Formfinding and determination of working drawings for a health spa in Bad Duerheim'. In: *Non-conventional Structures: Proceedings of the International Conference on the Design and Construction of Non-conventional Structures*, Vol. 1. May (B. H. V. Topping, eds), 125-131.

Grzelak, J. (1988) 'Conflict and cooperation'. In: *Introduction to Social Psychology*. (M. Hewstone, W. Stroebe, J.-P. Codol and G. Stephenson, ed.) NY: Basil Blackwell, 288-310.

Haider, G., Strutt, J. and Shier, J. (1975) 'Networks, structure and form'. *2nd International Conference on the Space Structures*, University of Surrey, Guildford, September, 655-662.

Hall, P. (1980) *Great Planning Disasters*. London: Penguin.

Happold, E. (1978) 'A personal perception of engineering'. *Architectural Design*, Profile 70, Introduction 5, 13-22.

Happold, E. and Dickson, M. (1974) 'Chandigarh. Munich 72'. *Architectural Design* 6 339-344.

Happold, E. and Liddell, W. (1975) 'Timber lattice roof for the Mannheim Bundesgartenschau'. *The Structural Engineer*, No3, Vol 53, 99-135.

Happold, E. and Liddell, W. (1976). 'Timber lattice roof for the Mannheim Bundesgartenschau. Discussion'. *The Structural Engineer*, No7, Vol 54, 247-257.

Happold, E., Ealey, T., Liddell, W., Pugh, J. and Webster, R. (1978) 'The design and construction of the diplomatic club, Riyadh. Discussion'. *The Structural Engineer*, Vol. 65A, No. 10, October, 377-382.

Happold, E., Ealey, T., Liddell, W., Pugh, J. and Webster, R., (1987) 'The design and construction of the diplomatic club, Riyadh'. *The Structural Engineer*. Vol. 65A, No. 1, January, 15-26.

Happold, E., Liddell, I. and Dickson, M. (1976) 'Design towards convergence'. *Architectural Design*, XLVI, July, 430-434.

Harley-Haddow, T. (1981) 'Structures in architecture'. *The Structural Engineer*, Vol. 59A, No. 6, June, 193-201.

Harré, R. and Secord, P. F. (1972) *The Explanation of Social Behaviour*. Oxford: Blackwell.

Haward, B. (1984) 'Hopkins at Cambridge'. *Architects' Journal*, 1, February, 40-47.

Herzberg, H. (1984) 'High Flyer'. *Architects' Journal*, 24 October, 43-63.

Hewstone, M. and Antaki, C. (1988) 'Attribution theory and social explanations'. In: *Introduction to Social Psychology*. (M. Hewstone, W. Stroebe, J.-P. Codol and G. Stephenson, ed.) NY: Basil Blackwell, 111-139.

Higgin, G. and Jessop, N. (1965) *Communications in the Building Industry. The Report of a Pilot Study*. London: Tavistock Publications.

Holden M. (1984) 'Acoustical fabric structures'. International Symposium on Architectural Fabric Structures. The Design Process, November, Orlando, Florida, USA, Proceedings Vol.1, 163-167.

Holgate, A. (1986) 'Lightweight structures and the appreciation of architecture'. In LSA 86: *Lightweight Structures in Architecture. The First International Conference on*

Lightweight Structures in Architecture. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 17-23.

Holgate, A. (1986) *The Art of Structural Engineering. An Introduction and Source book*. Oxford: Clarendon Press.

Holgate, A. (1988) 'The aesthetics of non-conventional structures'. In: *Non-conventional Structures: Proceedings of the International Conference on the Design and Construction of Non-conventional Structures*, Vol. 1. May (B. H. V. Topping, eds), 1-8.

Hunt, A (1992) 'The engineer as designer'. In: *The Art of the Structural Engineer*, B. Addis, London: The Building Centre Trust.

Huntington, C. (1984) 'Visual expression in fabric tension structures-the possibilities and the limitations'. *International Symposium on Architectural Fabric Structures. The Design Process*. Proceedings Vol. 1, Nov . Orlando, Florida. USA, 137-141.

IL 10, (1974) *Grid Shells*. Stuttgart: IL.

IL 21, (1979) *Form, Force and Mass*. Stuttgart: IL.

IL17, (1978) *The Work of Frei Otto and his Teams 1955-1976*. Stuttgart: IL.

Isenberg, D. (1986) 'Group polarization: A critical review and meta-analysis'. *Journal of Personality and Social Psychology*, 50, 1141-51.

Joedicke, J. (1963) *Shell Architecture*. London: Alec Tiranti.

Joedicke, J. (1985) *Space, Form and Architecture*. Stuttgart: Karl Kraenner Verlag, 61-69.

Kalay, Y. E. (1987) (Ed) *Computability of Design*. N.Y.: Willey, Interscience.

Kelly, P. , Kranzberg, M. , Rossini, F. Baker, N. ,Tarpley, F. Mitzner, M. (1986) 'Introducing innovation'. In Roy, R. and Wield, D. (Ed), *Product Design and Technological Innovation*. G. Britain: Open University Press, 10-17.

Kepes, G. (1969) *Language of Vision*. New York: Paul Theobald and Company.

Klein, B. (1992) In Calatrava, D. Sharp (eds), London: E and FN Spon, pp. 14-23.

Koehler, W. (1938) 'Gestalt problems', in Ellis, W. *A Source Book of Gestalt Psychology*. London Poutledge and Kegan Paul Ltd, 55-70.

Koehler,W. (1938) 'Physical gestalten', in Ellis, W. *A Source Book of Gestalt Psychology*. London Poutledge and Kegan Paul Ltd, 17-54.

Kullbach, V. and Olger, K. (1986) 'Investigation and erection of the saddle-shaped suspended, cable-tent and wooden shell roofs'. In LSA 86: *Lightweight Structures in Architecture. The First International Conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 580-587.

Lalvani, H. (1984) 'Generative morphology of curved space structures'. *International Symposium on Architectural Fabric Structures. The Design Process*. Proceedings Vol. 1, Nov . Orlando, Florida. USA, 142-150.

Lawson, B. (1980) *How Designers Think*. London: The Architectural Press.

Lawson, T (1992) 'Problems associated with wind and snow'. *Surface-stressed Building Structures*, International Association for Bridge and Structural Engineering, Henderson Colloquim, Pembroke College, Cambridge, 21-22 July.

Lehnert, S. (1992) 'PTFE, foils in air-supported structures'. *Surface-stressed Building Structures*, International Association for Bridge and Structural Engineering, Henderson Colloquim, Pembroke College, Cambridge, 21-22 July.

Lenczner, E. (1994) The design of the stone facade to the Pavilion of the Future, Expo '92, Seville. *The Structural Engineer*/ Vol. 72/ No 11/ 7 June 1994, 171-177.

Leonhardt, F. (1975) 'Looking back on 45 years as a structural engineer'. *The Structural Engineer*. March, No. 3, Vol. 54, 87-90.

Leonhardt, F. (1976) 'Looking back on 45 years as a structural engineer'. Discussion. *The Structural Engineer*. November, No. 11, Vol. 54, 451-456.

Leonhardt, F. and Schlaich, J. (1972) 'Structural design of roofs over the sports arenas for the 1972 Olympic Games: some problems of prestressed cable net structures'. *The Structural Engineer*. March, No 3, Vol. 50, 113-119.

Lincoln, Y. and Guba, E. (1985) *Naturalistic Inquiry*. London: Sage Publications.

Lipschutz, M. (1974) *Schaum's Outline of Theory and Problems of Differential Geometry*. New York.

Mackey, D. Special Issue on MBM (Martorell Bohigas Mackay). *On Diseno*, No 141, Barcelona, 168-169.

Mackinder, M. and Marvin, H. (1982) *The Design Process*. Institute of Advanced Architectural Studies. University of York, Jeremy Taylor.

Magee, B. (1973) Popper. London: The Woburn Press.

Mainstone, R. (1990) 'Hagia Sophia: Justinian's Church of divine wisdom, later the Mosque of Ayasofya, in Istanbul'. *The Structural Engineer*, Vol. 68, No. 4, 20 Feb., 65-70.

Maki, S. (1992) 'Metrodome stadium operations'. *Surface-stressed Building Structures*, International Association for Bridge and Structural Engineering, Henderson Colloquim, Pembroke College, Cambridge, 21-22 July.

Mark, R. (1990) *Light, Wind and Structure*. Cambridge: MIT Press.

Martin, J., Emmerson, R. and Berry, J. (1979) 'The structural engineer in a multidisciplinary practice'. *The Structural Engineer*. vol. 57A, No. 7, July, 213-221.

Mason, P. (1975) 'The structural engineer's significance'. *The Structural Engineer*. Dec, No 12, Vol. 53, 509-512.

McClinton, C., Brannon, D. and Maynard-Moody, S. (1979) 'Applying the logic of sample surveys to qualitative case studies: The case cluster method'. *Administrative Science Quarterly*, 24, 582-9.

Medlin, L. (1984) 'Prestressed tensile membrane design considerations'. International Symposium on Architectural Fabric Structures. The Design Process, November, Orlando, Florida, USA, Proceedings Vol.1, 126-136.

Miles, M. B. and Huberman, A. M. (1984) *Analyzing qualitative data: a source book for new methods*. Beverly Hills, CA: Sage.

Miller, G. A., Galanter, E. and Pribram, K. H. (1960) *Plans and Structure of Behaviour*. N.Y.: Holt, Rinehart and Winston.

Millington, W. (1966) *Dictionary of Mathematics*. London: Cassell.

Moreland, R. and Hogg, M. (1993) 'Theoretical perspectives on social processes in small groups'. *British Journal of Social Psychology*, 32, 1-4.

Morgan, G. and Smirich, L. (1980) 'The case for qualitative research'. *Academy of Management Review*, 5, 4, 49-50.

Mostyn, B. (1985) 'The content analysis of qualitative research. Data: A dynamic approach'. In M. Brenner, J. Brown and D. Canter (Ed.), *The research interview. Uses and approaches*. Florida: Academic Press, 115-145.

- Newcomb, T. (1953) 'Varieties of interpersonal attraction'. In: *Group Dynamics. Research and Theory*. London: Tavistock Publications, 104-119.
- Newell, A. (1970) 'Heuristic programming: Ill structured problems'. In: *Progress in Operations Research*, by J. Arnofsky (ed.) New York, Wiley.
- Newell, A. and Simon, H. A. (1972) *Human Problem Solving*. Edgewood Cliffs, New Jersey: Prentice Hall.
- Nicolin, P. (1989) Questions on Santiago Calatrava. In *Santiago Calatrava: Engineering Architecture*, Basel/Boston/Berlin: Birkhaeuser Verlag, pp. 27-30.
- Norberg-Schulz, C. (1985) *Intentions in Architecture*, first edition 1968.
- O'Neill, B. (1979) 'Two stage lift for Jeddah's big top'. *New Civil Engineer*. 21 June, 44-46.
- Otto, F. (1954) *Das Haegende Dach*. Berlin: Verlag Der Kunst Dresden.
- Otto, F. (1976). Thoughts on the construction of grid shells at Mannheim. In: *IL 13. Multicalle Mannheim*. Germany, 11-16.
- Oxman, R. and Oxman, R. (1992) 'Refinement and adaptation in design cognition'. *Design Studies*, April, Vol. 13, No. 2, Butterworth-Heinmann Ltd, 117-134.
- Page, J. K. (1963) Review of papers presented at the conference, conference on design methods, (eds. Jones, J C and Thornley, P G), Pergamon, Oxford (1964)
- Environmental research using models, *Architects' Journal*, 139, no 11, 11 March 1964.
- Pakinson, J. (1980) 'Munich's aviary net reaches for the sky'. *New Civil Engineer*, 20 March, 37-39.
- Parsons, W. B. (1968) *Engineers and Engineering in the Renaissance*. MIT Press.

Pink, J. (1992) Future Shock, *Architectural Review*, June 1992, Vol. CXC, No 1144, pp. 53-54.

Plemsus, G. (1984) 'From behaviour to meaning: on teaching membrane structures'. *International Symposium on Architectural Fabric structures. The Design Process*. Proceedings Vol. 1, Nov., Orlando, Florida. USA, 157-170.

Preiser, W. (1986) 'Human response to lightweight structures: a conceptual framework and research agenda'. In LSA 86: *Lightweight structures in Architecture. The first international conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 9-15.

Pugh, A. (1975) 'A brief introduction to tensegrity'. *2nd International Conference on the Space Structures*, University of Surrey, Guildford, September, 707-711.

Rice P. (1992) *Stone: Pavilion of the future, Seville: An Engineer Imagines*. London/Zurich/Munich: Artemis, pp. 119-126.

Rice, P. (1986) Engineers and architects working together with some examples of spatial and lightweight structures. In LSA 86: *Lightweight structures in Architecture. The first international conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 149-165.

Rice, P. (1992) *Exploring Materials. The work of Peter Rice Royal Gold Medallist 1992*. London: RIBA Gallery.

Rogers, E. (1986) 'Elements of diffusion'. In Roy, R. and Wield, D. (Ed), *Product Design and Technological Innovation*. G. Britain: Open University Press, 184-192.

Rowan Moore (eds) (1992) *Structure, Space and Skin. The work of N. Grimshaw and his partners*. London: Phaidon.

Sandaker, B. and Eggen, A. (1993) *The Structural Basis of Architecture*. London: Phaidon Press Ltd.

Schaefer, W. (1967) 'On the critical situation in a growing society'. *IL 3 Biology and Building*, Part 1, Stuttgart: IL.

Schierle, G. (1986) 'Design considerations for lightweight structures'. In LSA 86: *Lightweight structures in Architecture. The first international conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 166-175.

Semenetz, L. (1986) Shape, energy-concept and applications for tensioned membrane structures'. In LSA 86: *Lightweight structures in Architecture. The first international conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 287-311.

Severud, F, and Corbeletti, R. (1956) 'Hung roofs'. *Progressive Architecture*, March, 99-107.

Sharp, D. (1992) Santiago Calatrava: Building cultural buildings. In Calatrava, D. Sharp (eds), London: E and FN Spon, 8-13.

Shaw, M. (1971). *Group Dynamics. The Psychology of Small Group Behaviour*. USA: Library of Congress Cataloging in Publication Data.

Spaeh, H. and Spring, R. (1976) 'Stahbeton-Konstruktion der Gitterschalen'. IL 13: *Multihalle Mannheim*, Stuttgart: IL.

Spring, M. (1980) 'Strictly for birds'. *Building*, 18 August, 28-30.

Stadelhofen Railway Station, Zurich. Switzerland. In Calatrava, D. Sharp (eds), London: E and FN Spon, 32-35.

Stoecker, R. (1991) 'Evaluating and rethinking the case study'. *Sociological Review*, 88-112.

Strauss, A and Corbin, J (1990) *Basics of Qualitative Research. Grounded Theory Procedures and Techniques*. California: Sage Publications.

Struik, D. (1950) *Lectures on Classical Differential Geometry*. London: Addison Wesley Publishing Company, Inc.

Thornton, J. (1992) 'Membrane structures part 3, Getting design on site'. *Architects' Journal*, 16 September, 51-55.

Thornton, J. (1992) 'Part 1, Developing the form Membrane structures'. *Architects' Journal*, 23 September, 53-61.

Tischhauser, A. (1992) In Calatrava, D. Sharp (eds), London: E and FN Spon, pp. 24-31.

Tomlow, J. (1986) 'IL 34, Reconstruction of Gaudí's funicular model'. *Information of the Institute for Lightweight Structures*, University of Stuttgart.

Trachtenberg, M. (1983) 'Brunelleschi, Ghiberti, and 'L'occhio' minore of Florence Cathedral'. *Social Architectural Historians*, October, 42, 3, 249-257.

Wakefield, D. (1986) 'The development of an integrated CAD system for stressed membrane structures'. In LSA 86: *Lightweight structures in Architecture. The first international conference on Lightweight Structures in Architecture*. Sydney, Australia. 24-29 August, Proceedings Vol. 1, 271-279.

Wallach, M., Kogan, N. and Bem, D. (1953) 'Group influence on individual risk taking'. In: *Group Dynamics. Research and Theory*. London: Tavistock Publications, 430-443.

Weisberg, R. (1986) *Creativity, Genius and Other Myths*. N. York: W. H. Freeman and Company.

Werner, B. (1989) Extension, Stadelhofen Railway Station, Zurich, in Santiago Calatrava: *Engineering Architecture*, Basel/Boston/Berlin: Birkhaeuser Verlag, pp. 40-43.

Werner, B. (1989) Who is Santiago Calatrava?, in Santiago Calatrava: *Engineering Architecture*, Basel/Boston/Berlin: Birkhaeuser Verlag, pp. 7-14.

Wertheimer, M. (1938) Gestalt theory, in Ellis, W. *A Source Book of Gestalt Psychology*. London Poutledge and Kegan Paul Ltd. (pp. 1-11)

Wertheimer, M. (1938) The general theoretical solution, in Ellis, W. *A Source Book of Gestalt Psychology*. London Poutledge and Kegan Paul Ltd. (pp. 12-16) Addis, B. (a, 1992) *Tension Structures*. London: The Building Centre Trust.

Wilde, G. L. (1983) 'The skills and practices of engineering designers now and in the future'. *Design Studies*, vol.4, no 1, January, 21-33.

Wilke, H. and Knippenberg, A. V. (1988) 'Group performance'. In: *Introduction to Social Psychology*. (M. Hewstone, W. Stroebe, J.-P. Codol a,d G. Stephenson, ed.) NY: Basil Blackwell, 313-348.

Wilkinson, M. (1984) 'Lighting within air-supported structures'. *The Design of Air-supported Structures*, Bristol: Churchill Hall, The Institution of Structural Engineers/ The Chartered Institution of Building Services/ The Chartered Institute of Building/ The University of Bath, 282-292.

Williams, C. (1984) 'Form finding and cutting patterns for air-supported structures'. *The Design of Air-supported Structures*, Bristol: Churchill Hall, The Institution of Structural Engineers/ The Chartered Institution of Building Services/ The Chartered Institute of Building/ The University of Bath, 96-104.

Williams, C. (1984) 'The integration of wind tunnels testing and structural analysis of air-supported structures'. *The Design of Air-supported Structures*, Bristol: Churchill Hall, The Institution of Structural Engineers/ The Chartered Institution of Building Services/ The Chartered Institute of Building/ The University of Bath, 109-113.

Williams, C. (1990) 'The generation of a class of structural forms for vaults and sails'. *The Structural Engineer*, Vol. 68, no. 12, 19 June, 231-235.

Williams, H. A. (1993) 'Inventing tall storeys'. *Focus*, No 5, April , 6-10.

Wilson, T. D. (1985) 'Questionnaire design in the context of information research'. In M. Brenner, J. Brown and D. Canter (Ed.), *The research interview. Uses and approaches*. Florida: Academic Press, 65-77.

Yin, R. (1981) 'The case study crisis: some answers'. *Administrative Science Quarterly*, 26, 58-65.

Yin, R. (1984) *Case Study Research: Design and Methods*. Beverly Hills: Sage.

Zander, A. (1953) 'Group aspirations'. In: *Group Dynamics. Research and Theory*. London: Tavistock Publications, 419-429.

Zander, A. (1971) *Motives and Goals in Groups*. NY: Academic Press.

Zeisel, J. (1981) *Inquiry by Design*. NY: Cambridge University Press.

Zerbst, R. (1991) *Antoni Gaudí*. Spain: Taschen.

Mimeo

Boster, F. and Hale, J. (1990) 'Responsive scale ambiguity as a moderator of the choice shift'. *Communication Research*.

Bubner, E. (1972) *Zum Problem der Formfindung Vorgespannter Seilnetzflaechen*. IGMA Dissertanionen 2. Doctorate thesis Universitaet Stuttgart.

Fuhrmann, H. (1991) *Civil Engineering Design: Research, Education, and Practice*. Master of Science at the Massachusetts Institute of Technology.

Happold, E. (1989) 'Chariots of fire'. In Patterns 5, Buro Happold Office Literature, 2-7.

Happold, E. and Cook, M. 'Designing Tents—or The Computer as an Aid to Better Design.

Lyons, F.(1982) An Examination of Order in Cultural Symbol Systems with Particular Reference to Architecture. MPhil, Brighton Polytechnic.

Scheuermann, R. (1991) 'Tensile Structures And Their Use in Urban Context'. Thesis (M.A.) - University of Bath, 1991.

Schramm, W. (1971) 'Notes on case studies of instructional media projects'. Working paper for the *Academy of Educational Development* .

Torpiano, A. (1987) *On the design of masonry shell structures*. PhD thesis, University of Bath.

AN INSIGHT
INTO THE DESIGN PROCESS
OF UNCONVENTIONAL STRUCTURES.

VOLUME II - APPENDICES

Thesis submitted by Maria G. Voyatzaki
for the degree of PhD of the University of Bath.

1996

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Appendix 1. The questionnaire for the two pilot cases studies.

QUESTIONS

1. RELATION BETWEEN CLIENT AND DESIGN TEAM

- 1.1. Which member of the design team made arrangements with the client?
- 1.2. Did the client express any ideas about the way he/she wanted the building to be?
- 1.3. If yes, then what were these ideas and to what extent did the final decision follow these ideas?
- 1.4. If these ideas could not be followed, then why not?
- 1.5. How was the full brief developed with respect to client's wishes but lack of design knowledge?

2. BRIEF

- 2.1. How was the brief obtained?
- 2.2. Who was involved in the brief and what was that involvement?
- 2.3. Which were the strict and unchangeable issues that the design team had to take into account?
- 2.4. Who posed them?
- 2.5. Was an alternative offered outside the unchangeable ideas?
- 2.6. What was the client's main concern?
- 2.7. What were other designer's concerns?
- 2.8. Did the brief change during the design process? If yes, what were the reasons that dictated these changes?
- 2.9. If yes, then what were these changes?

3. TIME

- 3.1. What were the time-limits for the project?
- 3.2. Was time a major consideration for the design team in choosing a particular building type?
- 3.3. How long did the design process last?
- 3.4. How long did the construction period last?
- 3.5. Were there any delays according to the original schedule? If yes, what were these delays attributed to(i.e. Design or Construction)?

4. COST

- 4.1. Was there a certain budget determined to cover the project?
- 4.2. When was this budget determined and by whom?
- 4.3. If yes, how much did that affect the decision on a certain building type?
- 4.4. What was the maintenance cost(high or low, in long terms or initially)?

- 4.5. What was the energy cost predicted (high or low, in long terms or initially)?
- 4.6. What was the capital cost of the structure; heating, cooling and ventilation equipment, cladding, finishes, etc. as a percentage?
- 4.7. Were there any unavoidable overrun costs? If yes, what was the reason why they were not predicted?
- 4.8. If yes, what were the consequences?

5. ENVIRONMENTAL, PLANNING AND URBANISTIC CONSIDERATIONS

- 5.1. Did the urban site constrain the choice of the final decision?
- 5.2. Did the climate affect that decision?
- 5.3. Did earthquake, wind and snow conditions affect that decision?
- 5.4. How was the building adapted to the environment?
- 5.5. How were transportation and access accommodated in the design?

6. DESIGN TEAM

- 6.1. How many different disciplines or other specialists were involved?
- 6.2. Had the members of the design team collaborated on other projects in the past?
- 6.3. Were there any particular disciplines that were invited to solve particular problems? If yes, which were they, and what exactly did they offer?
- 6.4. What was the degree of contribution of different disciplines based on the criteria of time spent and fees paid?
- 6.5. Were there disagreements between the members of the design team?
- 6.6. If yes, what were they? Whose ideas were dominant and why?

7. DECISION MAKING ON THE STRUCTURAL TYPE

- 7.1. Were the alternative structural forms which were proposed?
- 7.2. If yes, who proposed these alternatives?
- 7.3. Was there a justification for each one?
- 7.4. Which was the one that the design team decided on?
- 7.5. What made that solution better than the others and why were the others rejected?
- 7.6. Did the idea derive from the use of "design idioms" traditional to the office? If yes, which were they?
- 7.7. Did traditional, local architecture affect the choice of the structural type?
- 7.8. Was the inspiration, a product of exploration of a new language?
- 7.9. To what extent were technical references such as national (DIN, BS, etc.) standards and building regulations used in the design process?
- 7.10. What was the response of that structural form to wind, snow and earthquake loads?
- 7.11. Did the form of the structure affected that response?
- 7.12. To what extent did the form of the structure affected that response?
- 7.13. Did the choice of the structural affect the choice of the environmental systems (lighting, ventilation, cladding, etc.)?

- 7.14. How did the choice of the structural affect the choice of the environmental systems (lighting, ventilation, cladding, etc.)?

8. MATERIAL

- 8.1. At what stage of the design process was the decision for the type of material employed made?
- 8.2. Which members of the design team made that decision?
- 8.3. Which were the criteria for that choice?(economy, availability, durability and strength)
- 8.4. Was that material the most suitable for that particular structural type? If yes, then why?
- 8.5. If no, then which other materials could be employed for the same structural form?

9. BUILDABILITY AND DETAILS (ARCHITECTURAL AND STRUCTURAL)

- 9.1. How important was the design of details, when did it start and how did it evolve?
- 9.2. Were standardised components employed on the design of details?
- 9.3. If no, then why not?
- 9.4. If yes, then what was the proportion between the use of standardised and newly designed components?
- 9.5. What proportion of details was proposed by the design team and what by the fabricator?
- 9.6. Did detailing of boundary conditions and secondary structures affect the final decision?
- 9.7. How did detailing of boundary conditions and secondary structures affect the final decision?

10. TOOLS USED DURING THE DESIGN PROCESS

- 10.1. What were the means employed to communicate at various stages of the design process:
- A. the choice of the structure
 - a. within the design team and
 - b. between the client and the design team?
 - B. the architectural concept
 - a. within the design team and
 - b. between the client and the design team?
- 10.2. To what extent could physical models fulfil this communication?
- 10.3. Which was the best means to visualize the geometry of the structure? (drawings, physical or computer models)
- 10.4. What kind of tests were undertaken during the design process? (structural, acoustical, thermal, wind and lighting tests)
- 10.5. What was the degree of accuracy of these tests?

- 10.6. To what extent were models reliable?
- 10.7. At what stage was computer simulation used?
- 10.8. Were there other mathematical calculations necessary for the form-finding ?
- 10.9. To what extent did experience from other projects assist the progress of the design process?

Appendix 2. The interview guide for the seven case studies following the two pilot studies.

1. **RELATION BETWEEN CLIENT AND DESIGN TEAM**

 -Inquiry into the involvement of the client and contact with team.
2. **BRIEF**

 -how loose or tight and strict, what changes occurred.

 -who determined these changes if any, or who imposed strict restraints.
3. **TIME**

 -was it a problem. if yes what caused it.
4. **COST**

 -was it a problem. if yes what caused it.
5. **ENVIRONMENTAL, PLANNING AND URBANISTIC CONSIDERATIONS**

 -to what extent they were taken into account.
6. **DESIGN TEAM**

 -relationships among members, involvement, contribution.
7. **DECISION MAKING ON THE STRUCTURAL TYPE**

 -who decided when and why that solution was preferred.
8. **MATERIAL**

 -who decided when and why that solution was preferred.
9. **BUILDABILITY AND DETAILS (ARCHITECTURAL AND STRUCTURAL)**

 -who was involved and when it was decided.
10. **TOOLS USED DURING THE DESIGN PROCESS**

 -communication

-simulation.

11. EVALUATION

-Was the selection of the structural form successful:

- a. from an architectural point of view?
- b. from a structural point of view?
- c. from an environmental point of view?

-Which were the most significant problems encountered during the design process?

-Which member of the design team solved these problems?

-Were there any unforeseen problem during erection? How were they solved?

-What could be the lesson that a designer could draw out of this project?

-Question about the information the interviewee gets from engineers or architects (whatever is appropriate).

-What would be given to advice a young designer.

-Overview of issues: Education of architects and engineers. Encouragement of additional comments.

Appendix 3. Computer program.

Computer programs involving static equilibrium with dynamic relaxation or matrix methods are the most efficient and fast ways of form finding (Barnes 1984, 1988). The efforts of different researchers have been focused on ways to make these programs user friendly. In an effort to gain some understanding of the philosophy of these computer programs the researcher wrote a number of computer programs. The programs were written in the 'C' language and were implemented in the UNIX operating system.

Both differential geometry and structural topology have contributed to the development of the cutting pattern process. This process determines the lengths of all the cables or dimensions of fabric pieces. The theory of developable surfaces is applied in the cutting pattern process.

The theory of dynamic relaxation was first proposed by Alistair Day in 1965. As Ove Arup (1983), stated the theory is based on the fact that a structure must move in order to get from one state of equilibrium to another. This theory employs Newton's second law, which describes the principles of dynamic equilibrium of a node:

$$\text{Mass} \times \text{Acceleration} + \text{Damping} \times \text{Velocity} + \text{Stiffness} \times \text{Displacement} = \text{Externally Applied Forces}$$

Residual forces are defined as the difference between the external and internal forces on a node. Nodal co-ordinates are updated thus:

$$\text{New position} = \text{Old position} + \text{Time Interval} \times \text{Velocity of Node}$$

At the next stage the new nodal residual forces can be calculated.

A combination of two programs was produced containing graphics and structural analysis. The structural analysis uses dynamic relaxation and can be applied to a cable net in three dimensions. .

Appendix 4. Physical modelling.

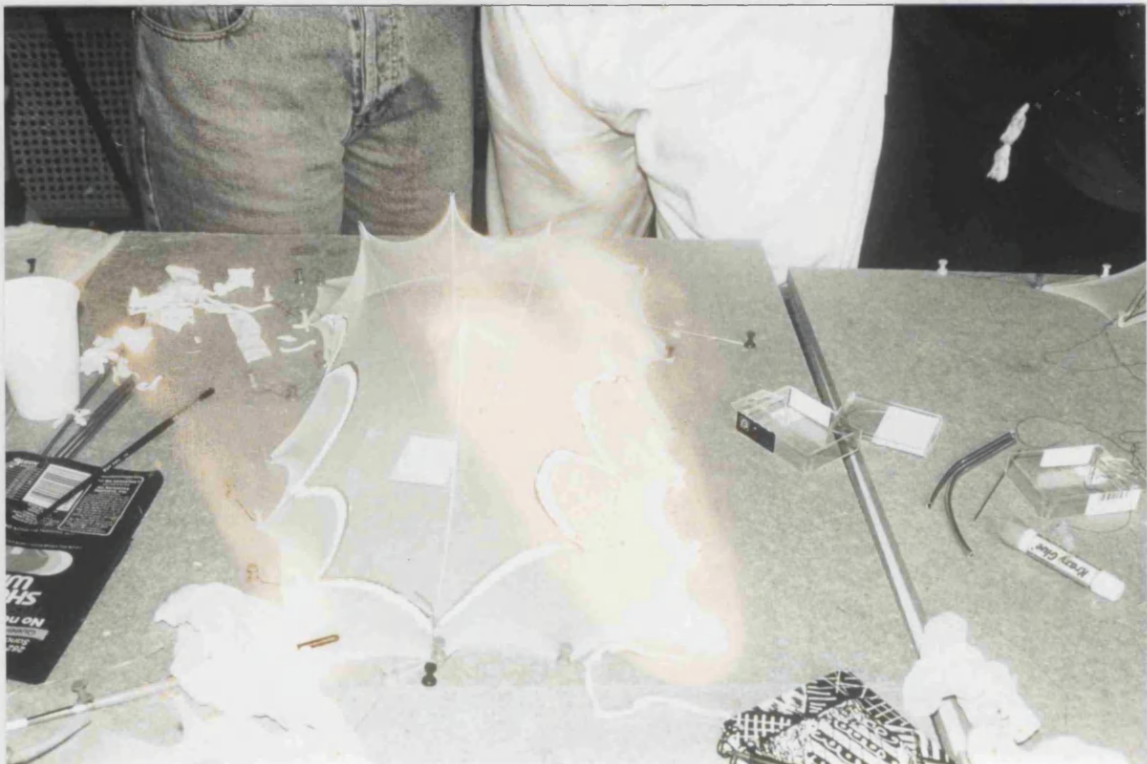
Happold and Cook (mimeo) have explained that there is 'still no practicable substitute for a carefully built aeroelastic model tested in a wind tunnel to understand the dynamic behaviour of a flexible structure'[...]'Physical models using soap films or stretchy membranes are quite effective at providing an adjustable medium to assist decisions on final form. But they do not let themselves to easy load analysis, accurate measurement or even walk-through perspective views' (ibid).

Soap bubbles have been used to also represent very light tents and air halls (Otto 1987). "Wire net models, fine woven and knitted fabrics, grid tulles as well as thin rubber membranes" have certain limits of manipulation with regards to the degree of stress within their surface" (p.14, ibid). The advantage of soap bubbles is that they achieve a good approximation of minimal surfaces (equal stress in any direction of their surface). Unconventional structures with unequal stresses tend to fold and strain "more at the points subject to higher loads until they tear or adopt forms which deviate strongly from the original cutting patterns" (p.15, ibid). The disadvantage of soap bubbles is that they do not last longer than the time to be taken a photograph, from which the degree of curvature can be estimated.

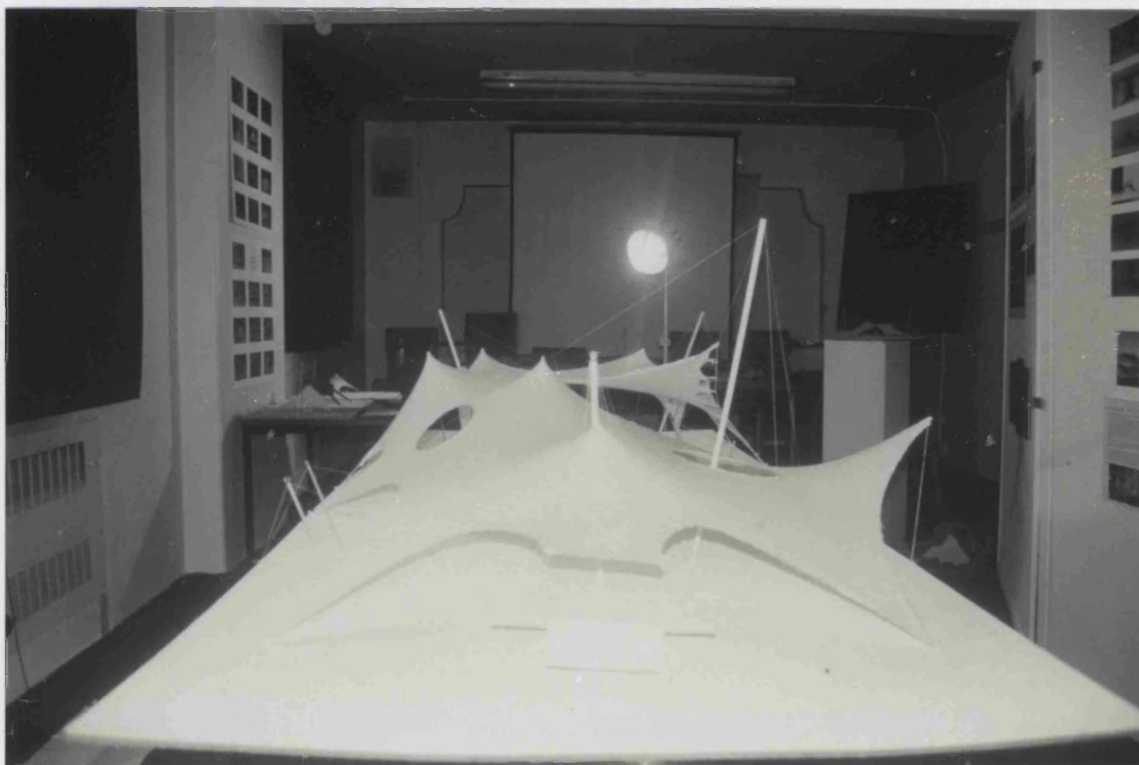
Nowadays, physical modelling with tights and other materials is still popular. A recent workshop at Buro Happold on physical modelling took place in order to update designers on the technique. To simulate a fabric structure, nylon tights are required. The tights, once cut into a single piece, are stretched across a base board and secured with pins. This helps to stretch the nylon fabric ready to create the required form. The compressive elements -masts, arches, trusses, etc. - are then erected at the desired points and 'anchored' with pins for stability and security. Cotton is then threaded from the 'anchoring' points –from the inner side of the surface– to the mast or other tops, down to the diametrically opposite anchorage. That is repeated on all anchorages so that a 'flexible' surface is formed.

By pulling the threads from at anchoring positions the designers can change the curvature of the form. The variations are infinite. After the designer is satisfied with the form, the outline or boundaries of the form have to be determined. With a pen the designer draws the boundaries on the edge of the tights, which must be then stitched and super-glued for reinforcement. Once the glue has dried, the fabric can be trimmed on the stitched side. The photographs that follow were taken during the workshop at Buro Happold and at a workshop with third year architectural students at Plymouth University.









Appendix 5. Differential geometry.

Most practitioners in the field of unconventional structures, both architects and engineers have no knowledge of differential geometry. However, a greater insight into such fields as cutting patterns generation can be gained from the study of differential geometry.

Classical differential geometry is the branch of geometry which studies the fundamental concepts of the theory of curved lines and surfaces in three-dimensional space. The term 'differential' is used because differential calculus is used to investigate the way in which the line or surface curves.

Millington (1966) defines a surface as 'a set of points forming a space which has only two dimensions. The surface may be planar or curved' (p.229).

Fabric structures, masonry vaults, cable nets and concrete, plastic and metal shells approximate to a curved surface.

Gauss has defined the curvilinear coordinates of a point on a surface as two parameters in terms of which the precise position of a point on a surface can be calculated. The curvature of a surface is studied by examining how the direction of the normal to the surface varies on the surface (Struik 1950).

When the Gaussian curvature is positive, then the centres of curvature of the normal sections are all on the same side of the surface. The point is called an elliptic point of the surface and an example is any point on an ellipsoid. If the Gaussian curvature equals zero, the point is called parabolic. An example is any point on a cylinder. Lastly, if the Gaussian curvature is negative, the centres of curvature of the normal sections lie on either side of the surface. The point is called hyperbolic and it can be any point on a saddle shape.

Surfaces of positive gaussian curvature are called synclastic and surfaces of negative Gaussian curvature require 'orange segment' shaped panels, wider in the middle, while surfaces of negative Gaussian curvature require panels which are narrower in the middle.

Onle developable surfaces which have zero Gaussian cuvature can be formed from straight sided panels.

Appendix 6. Example of open coding

INTERVIEW WITH A'3.

M. "When did you and your colleague get involved, which stage of the design process?"

A'3. "It was very early, because it was a curious situation in the beginning. E3 had constructed in the original design, a normal building with cantilevered structures. A short time before the end of the competition they thought: "it is always the same thing what we are doing and the same thing what other people will do." They thought that it should be done in a total other way. And then they started the work and the very simple thing they put a net of stocking with some sticks on ground and make a biaxially curved structure very roughly with the model. They made some sketches and then they won the competition. The reason was, that is the explanation, I don't know exactly what it is, the famous architect from Karlsruhe, he was the head of the jury of that competition and he thought that it is my colleague and then he said that this should be the first prize, because he thought it is good, and therefore my colleague should get first prize."

M. "What did he think that your colleague was the person to get the first prize?"

A'3. "Well, it was a structure, which was connected with my colleague, it was an obvious, expected way to think. And AP3 won the competition and he had no idea about this structure, and he had only the idea, that it should be this way. Then E3 was a very clever man and he asked immediately all these people to help him to avoid these people who could be in the future against him, to say what you are doing is wrong, he put to take these people on his side, and there was a short time after the competition in Berlin, a 'phone call and I had EP3 and asked me to tell my colleague that he wanted to work with him and he wants my colleague and his group as a consultant."

M. "Were the people from the jury that got on his side?"

A listing of the program follows:

```
#include <stdio.h>
#include <math.h>

#define DIMENSION 10
#define VEC_PRO(a, b) (a.x*b.x + a.y*b.y + a.z*b.z)

FILE *fred;    /**name of file:coordinates, number of nodes, x, y, z**/
FILE *maria;   /**name of file:Members, number of member, starting, finishing p
FILE *load;
FILE *terj;    /**tri**/
FILE *monitor;
FILE *roger;   /** newcoordinates**/

main()
{
    float x[DIMENSION], y[DIMENSION], z[DIMENSION];
    float loadx[DIMENSION], loady[DIMENSION], loadz[DIMENSION];
    float fx[DIMENSION], fy[DIMENSION], fz[DIMENSION];
    float L0[DIMENSION], L[DIMENSION], T[DIMENSION], EA[DIMENSION],
        TenCoef, SurfTen[DIMENSION];
    float adota, bdotb, cdotc, adotb, bdota, bdotc, cdotb, cdota, adotc;
    float fxt, fyt, fzt, deltax, deltay, deltaz;
    float temp1, temp2, temp3;
    double sqrt();
    int d[DIMENSION], e[DIMENSION], A[DIMENSION], B[DIMENSION], C[DIMENSION];
    float SumOfSquares, constant;
    int NumberOfCycles, NumberOfNodes, NumberOfMembers, LoadedNodes,
        NumberOfTri;
    int NumberOfCoordinates, Cycle, Node, Member, Tri;
    int FixedOrFree[DIMENSION], CompOrNot[DIMENSION];

    struct Vector {
        float x, y, z;
    } a, b, c;

    monitor=fopen("soap1.mon", "w");  /***/

    fred=fopen("coordinates", "r");
    fscanf(fred, "%d", &NumberOfNodes);

    for(i=0; i<=NumberOfNodes-1; i+=1)
    {
        fscanf(fred, "%d", &Node);
        fscanf(fred, "%f%f%f%d", &x[Node], &y[Node], &z[Node],
            &FixedOrFree[Node]);
    }
    fclose(fred);

    for(Node=0; Node<=NumberOfNodes-1; Node+=1)
    {
        loadx[Node] = 0.0;
        loady[Node] = 0.0;
        loadz[Node] = 0.0;
    }
}
```



```

load=fopen("load", "r");
fscanf(load, "%d\n", &LoadedNodes);
fprintf(monitor, "LoadedNodes is %d\n", LoadedNodes);
/* printf("LoadedNodes is %d\n", LoadedNodes);*/

for(i=0; i<LoadedNodes; i+=1)
{
    fscanf(load, "%d", &Node);

    fscanf(load, "%f%f%f\n", &loadx[Node], &loady[Node], &loadz[Node]);
/*    printf("%d %f %f %f\n", Node, loadx[Node], loady[Node], loadz[Node]);*/
}

maria=fopen("Members", "r");
fscanf(maria, "%d\n", &NumberOfMembers);

for(i=0; i<=NumberOfMembers-1; i+=1)
{
    fscanf(maria, "%d ", &Member);
    fscanf(maria, "%d %d ", &d[Member], &e[Member]);
    fscanf(maria, "%f %f %d\n", &L0[Member], &EA[Member],
                                &CompOrNot[Member]);
}

fclose(maria);
terj = fopen("tri", "r");
fscanf(terj, "%d\n", &NumberOfTri);
fprintf(monitor, "NumberOfTri = %d\n", NumberOfTri);
for(Tri=0; Tri<NumberOfTri; Tri++)
{
    fscanf(terj, "%d", &Tri);
    fscanf(terj, "%d%d%d%f\n", &A[Tri], &B[Tri], &C[Tri], &SurfTen[Tri]);
}
fclose(terj);

Question:printf("\n NumberOfCycles = ");
scanf("%d", &NumberOfCycles);
fprintf(monitor, "NumberOfCycles= %d\n", NumberOfCycles); /**/

if(NumberOfCycles==0)
    goto finish;
printf("constant = ");
scanf("%f", &constant);
fprintf(monitor, "constant = %f\n", constant);/***/
for(Cycle=0; Cycle<=NumberOfCycles-1; Cycle+=1)
{
    for(Node=0; Node<=NumberOfNodes-1; Node+=1)
    {
        fx[Node] = loadx[Node];
        fy[Node] = loady[Node];
        fz[Node] = loadz[Node];
    }
    for(Member=0; Member<=NumberOfMembers-1; Member+=1)
    {
        deltax = x[e[Member]]-x[d[Member]];
        deltay = y[e[Member]]-y[d[Member]];
        deltaz = z[e[Member]]-z[d[Member]];
        L[Member] = (float)sqrt((double)((deltax*deltax)+(deltay*deltay)+(deltaz*deltaz));
        if(T[Member]<0.0)
        {
            if(CompOrNot[Member]==0)
                T[Member]=0.0;
            T[Member] = EA[Member]*(L[Member]-L0[Member])/L0[Member];
            TenCoef = T[Member]/L[Member];

            fxt = deltax*TenCoef; /**out of balance forces**/
            fyt = deltay*TenCoef;
            fzt = deltaz*TenCoef;

            fx[d[Member]] += fxt;
            fx[e[Member]] -= fxt;
            fy[d[Member]] += fyt;

```

```

    fy[e[Member]] -= fyt;
    fz[d[Member]] += fzt;
    fz[e[Member]] -= fzt;
}

for(Tri=0; Tri<=NumberOfTri-1; Tri++)
{
    a.x = x[C[Tri]]-x[B[Tri]]; /*x2-x1*/
    a.y = y[C[Tri]]-y[B[Tri]];
    a.z = z[C[Tri]]-z[B[Tri]];

    b.x = x[A[Tri]]-x[C[Tri]];
    b.y = y[A[Tri]]-y[C[Tri]];
    b.z = z[A[Tri]]-z[C[Tri]];

    c.x = x[B[Tri]]-x[A[Tri]];
    c.y = y[B[Tri]]-y[A[Tri]];
    c.z = z[B[Tri]]-z[A[Tri]];
    printf("%f %f %f %f %f %f %f %f %f\n", a.x, a.y, a.z, b.x, b.y, b.z,
                                              c.x, c.y, c.z);

    adota = VEC_PRO(a, a);
    bdotb = VEC_PRO(b, b);
    cdotc = VEC_PRO(c, c);
    printf("%f %f %f\n", adota, bdotb, cdotc);

    adotb = VEC_PRO(a, b);
    bdota = adotb;

    bdotc = VEC_PRO(b, c);
    cdotb = bdotc;

    cdota = VEC_PRO(c, a);
    adotc = cdota;

    temp1 = SurfTen[Tri]/(2.0*(float)sqrt((double)(adota*bdotb-adotb*adotb)));
    temp2 = bdotb+adotb;
    temp3 = adota+adotb;

    fx[C[Tri]] += temp1*(-temp2*a.x+temp3*b.x);
    fy[C[Tri]] += temp1*(-temp2*a.y+temp3*b.y);
    fz[C[Tri]] += temp1*(-temp2*a.z+temp3*b.z);

    temp1 = SurfTen[Tri]/(2.0*(float)sqrt(bdotb*cdotc-bdotc*bdotc));
    temp2 = cdotc+bdotc;
    temp3 = bdotb+bdotc;

    fx[A[Tri]] += temp1*(-temp2*b.x+temp3*c.x);
    fy[A[Tri]] += temp1*(-temp2*b.y+temp3*c.y);
    fz[A[Tri]] += temp1*(-temp2*b.z+temp3*c.z);

    temp1 = SurfTen[Tri]/(2.0*(float)sqrt(cdotc*adota-cdota*cdota));
    temp2 = adota+cdota;
    temp3 = cdotc+cdota;

    fx[B[Tri]] += temp1*(-temp2*c.x+temp3*a.x);
    fy[B[Tri]] += temp1*(-temp2*c.y+temp3*a.y);
    fz[B[Tri]] += temp1*(-temp2*c.z+temp3*a.z);
    printf("%f %f %f %f %f %f %f %f %f\n", fx[A[Tri]], fy[A[Tri]], fz[A[Tri]],
        fx[B[Tri]], fy[B[Tri]], fz[B[Tri]],
        fx[C[Tri]], fy[C[Tri]], fz[C[Tri]]);
}
SumOfSquares = 0.0;

```

```

for(Node=0; Node<NumberOfNodes; Node++)
{
    if(FixedOrFree[Node]==1)
    {
        x[Node] += constant*fx[Node];
        y[Node] += constant*fy[Node];
        z[Node] += constant*fz[Node];
        SumOfSquares += fx[Node]*fx[Node]+fy[Node]*fy[Node]+fz[Node]*fz[Node];
        fprintf(monitor,"SumOfSquares = %f\n", SumOfSquares);
    }
}
printf("SumOfSquares = %f\n", SumOfSquares);

goto Question;
finish:
fred=fopen("newcoordinates", "w");

fprintf(fred, "%d\n", NumberOfNodes);

for(Node=0; Node<=NumberOfNodes-1; Node+=1)
{
    fprintf(fred, "%d %f %f %f %d\n",
            Node, x[Node], y[Node], z[Node], FixedOrFree[Node]);
}
/**printf("%d %f %f %f", &Node, &x[Node], &y[Node], &z[Node]);**/
fclose(fred);
close(monitor);
}

```

```

LoadedNodes is 7
NumberOfCycles= 3
constant = 0.500000
NumberOfTri = 6
SumOfSquares = 0.984120
NumberOfTri = 6
SumOfSquares = 1.938327
NumberOfTri = 6
SumOfSquares = 2.866074
NumberOfCycles= 3
constant = 0.400000
NumberOfTri = 6
SumOfSquares = 3.768055
NumberOfTri = 6
SumOfSquares = 4.649942
NumberOfTri = 6
SumOfSquares = 5.512158
NumberOfCycles= 3
constant = 0.400000
NumberOfTri = 6
SumOfSquares = 6.355120
NumberOfTri = 6
SumOfSquares = 7.179235
NumberOfTri = 6
SumOfSquares = 7.984903
NumberOfCycles= 3
constant = -0.500000
NumberOfTri = 6
SumOfSquares = 8.772515
NumberOfTri = 6
SumOfSquares = 9.582469
NumberOfTri = 6
SumOfSquares = 10.415364
NumberOfCycles= 3
constant = 0.400000
NumberOfTri = 6
SumOfSquares = 11.271816
NumberOfTri = 6
SumOfSquares = 12.109136
NumberOfTri = 6
SumOfSquares = 12.927728
NumberOfCycles= 3
constant = -0.500000

```

```

NumberOfTri = 6
SumOfSquares = 13.727990
NumberOfTri = 6
SumOfSquares = 14.550934
NumberOfTri = 6
SumOfSquares = 15.397168
NumberOfCycles= 4
constant = -0.600000
NumberOfTri
LoadedNodes is 7
NumberOfTri = 6
NumberOfCycles= 5
constant = 0.100000
SumOfSquares = 1.000000
SumOfSquares = 0.360001
SumOfSquares = 0.129602
SumOfSquares = 0.046657
SumOfSquares = 0.016797
NumberOfCycles= 0

```

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M. "Were the people from the jury that got on his side?"

A3. "I was at that time in our studio, working with my colleague and we started immediately to prepare this rough idea, into a structure, into a model, into a design which is discussable with the engineers, you see? This other thing was only the idea and architects were able to talk about this but not the engineer; "it is too large, it is not enough curvature" and this was a big joke, we did a big part in six weeks, in a small office in Berlin with roughly eight people, and we worked day and night and we drew sections of the stadium to study different types of the roof, lower roof, middle height, very high roofs."

M. "Were all these hand drawings or models?"

A3. "Models and drawings. Models with fabrics, and an overall model of this stadium, of the sports centre and the swimming hall, and after that it was necessary to decide for the Olympic Society, who was responsible for the Olympic building, and all these people from the government in Munich were also involved with that and they had to decide if it is possible to build that structure in such a way, or not. Because most of the people which had a responsibility had the idea that this is too much future, this is not possible to build, and also engineers, well-known engineers felt that it is not possible, and it is too flexible, we have no idea about the lifespan, is is not comparable with the German pavilion in Montreal, that is very small, and this is very big and really it was a step, that it was very big, it would be better to have a step in between, these were only 8,000 sq. m. in Montreal and this is 80,000 sq. m , and a step of 20,000 sq.m., 50,000 sq.m. would be better, to get more information. And normally, it is right that if you get the job, you have to construct, to design and you have not to make developments, research work, but it was necessary, and that needs a lot of time, and it needs a lots of people to do that, and all this job had been done in the Institute of Lightweight Structures in Stuttgart. There sometimes eighty people, but from all type of disciplines. Students from different types of disciplines, engineers, architects, all people. Sometimes it was not necessary to explain what they have to do, it was really a psychological job to say: "you are a good man or you are a good girl. Please do this

and do that.” They had no idea about that, but there should be a group which work day and night, because the time was very short. And we made several groups, one for the stadium, one for the sports hall, for the swimming hall and so on, one only for the details, one only for the roof cladding, and all these groups had its own head, the building engineers or architects. And I was the manager of all these groups and I had to go to Munich all the time and look for the money. And nobody knows what is the next step. And I always had to explain in Munich, this is the next step and for this next step you need such money and such money, this money and that money.”

M. “Did you know what you were doing?”

A’3. “Yes, we talked about it with my colleague before, you see? My colleague was a little outside of this direct management. He knows a lot about these special things, and always when it was difficult he discussed these problems with his engineers. But my colleague and I, we had a special consultant job, this is one thing, and the other thing was research work at the Institute, only for the Institute. But the head of the Institute was my colleague, too. So it was separate. I was working as a consultant but this consultancy work includes all the supervision of this work. That was the situation. Then that goes step by step that the architects tried to understand the situation of the structure, the engineer too. There was a very little knowledge about these structures at the beginning. At the end everybody knows a lot of things, especially the engineers. At the beginning, there were sometimes curious ideas about making the structures, and concerning the architectural problem it was the architects for instance, some people from the AP3 group had too much idea about the shape and the form, and not about the behaviour of the total construction. When they said, for instance, “we want to have such and such a shape”, and we said; “we have to change a little, and this has a better behaviour in relation to the forces and in relation to the structure”, they said; “no, we want this one only”. They are only working with the optical point of view without trying to understand the background of the structural behaviour. To find out the structural behaviour, the shape is finally the result of this and not the aim.

M. "What were the EP3 team doing while you were working in the IL?"

A3. "AP3 had also different groups. They are working, for instance, one group for the stadium, for the sports hall and for the the swimming hall, but these were the groups designing all these structures which are independent from the roof. And they had a roof group for the roof and with this group, the head of this was the architect , we had the discussions. And all the discussions which were important we are in connection with the architect and the engineer. Then the shape changed the forms, or they give new ideas and said: "we want to have....."

OPEN CODING ON A3's INTERVIEW, MUNICH OLYMPIC ROOFS.

(1st page, §2)

category

seeking advice from an expert as a result of lack of understanding on a winning conceptual scheme, which won the competition for it was erroneously taken as the product of an expert.

"Well, it was a structure, which was connected with my colleague, it was an obvious, expected way to think. And EP3 won the competition and he had no idea about this structure, and he had only the idea, that it should be this way."

category

preparing a model after receiving the rough scheme

property

legibility, degree of detail and resolution

category

-adding information to the existing rough ideas

-preparing the soil for discussion with engineers

“and we started immediately to prepare this rough idea, into a structure, into a model, into a design which is discussable with the engineers.”

-differentiating the language(p.1 §3)

“This other thing was only the idea and architects were able to talk about this but not the engineer; ‘it is too large, it is not enough curvature’

-involvement of authorities and degree of uncertainty and doubt (p2 §2)

“all these people from the government in Munich were also involved with that and they had to decide if it is possible to build that structure in such a way, or not. Because most of the people which had a responsibility had the idea that this is too much future, this is not possible to build, and also engineers, well-known engineers felt that it is not possible, and it id too flexible”

-lacking knowledge, increasing uncertainty

we have no idea about the life span, is is not comparable with the German pavilion in Montreal, that is very small,

-using precedent building as examplers

“and this is very big and really it was a step, that it was very big, it would be better to have a step in between, these were only 8000sq.m. in Montreal and this is 80 000sq.m, and a step of 20 000sq.m., 50 000sq.m. would be better, to get more information”

category

-reducing difficulty

-introducing a bigger design team

-spending more time on the design process

-using expertise

-dividing the group into different units working on particular issues

“and that needs a lot of time, and lots of people to do that, and all this work has been done in the Institute of Lightweight structures in Stuttgart, and there sometimes eighty people, but from any disciplines, students from different types of disciplines, engineers, architects...Sometimes it was not necessary to explain what they have to do, it was really a psychological joke, to say that you are a good man, please do this or that, they had no idea about that, but they should be a group, they should work day and night, because the time was very short, and we made several groups, one for the stadium, one for the swimming hall and so on, one only for the details, one for the roof cladding, and all these groups had their own head, the engineers or architects and I was the manager of all these groups and I had to go to Munich all the time and look for the money”

category

-facing the uncertainty, when the next step is not known due to the peculiarity of the project

“And nobody knows what is next.”

category

-advancing the design process by consultation and research (bottom of p.2)

“My colleague and I had a special consultant, this is one thing, and the other thing was research work at the Institute, only for the Institute, so I was working as a consultant and this consultancy includes all the supervision of this work”

Appendix 7 Interviews with leading practitioners

Interview with Birkin Haward

1 BH: This is the second round of interviews ?

2 MV: Yes that's right.

3 BH: And you've already talked to some people ?

4 MV: No you're the first one.

5 BH: Who else are you seeing ?

6 MV: I'm seeing Robin Snell who worked with Michael Hopkins
on the Glyndebourne Opera.

7 BH: He is very good, sounds very good.

8 MV: Do you think that the dual architectural and engineering nature
of unconventional structures influences the design process itself?

9 BH: I am not sure what you mean by that question really. Maybe
we'll come back to that.

10 MV: Do you think that the architectural language of unconventional
forms is different from that for conventional and that influences the
process ?

Q1

Q2

11 BH: Yes, I've read this and I think that the problem I have - I have done a number of unconventional structures - I worked with Fosters for a long while, I don't know if Adie told you that, but I worked with Norman for thirteen or fourteen years and we did do some, what you might call unconventional structures. But certainly our work here since then, I would think that they weren't particularly unconventional. I think the problem is, I don't quite know where you draw the line. I think for me there is just structure. Sometimes it turns out to be what you would call unconventional in the sense that what you are trying to do, you may have to try to look at ways of doing things that people haven't done before.

line of
demarcation
between
conventional
and
unconvention
al structures

12 BH: But there is a question down here no. 11, which comes first unconventional structures requiring close collaboration between engineers and architects, or does close co-operation come first, in order for unconventional structures to be produced.

13 BH: I mean that is an interesting question because I think in a way, I don't think people set out to design unconventional structures in themselves, do they ?

14 BH: Unless you have got some examples that I could see.

15 MV: Well it is very rare that it is an end in itself, it's true.

16 BH: You might decide to do it for slightly strange reasons, like it's an exhibition building or something and that part of the brief, that it should be rather strange. I don't think that is where you really begin, do you?

use of the
building
calling for
something
unconvention
al?

17 MV: No I don't think so either. What the question is trying to ask here is whether the outcome of the collaboration is more than likely to be an unconventional structure, or it works the other way round that perhaps an architect comes up with a strange idea and the help of an engineer materialises it.

18 BH: Yes that's possible I suppose. I think it depends how different groups of people work together and that's something else you touch on. I don't know what you found, but certainly our experience is that we always work in groups and I wouldn't say that we as architects design something and then ask the engineers to look at it, it is done round this table, or round other tables from the beginning. I don't know whether you have found that to be common practice amongst the other people you have talked to but certainly I thought that was the way that Ted used to design and certainly worked with Arups and Hunt when I was with Fosters, that is certainly the way we worked.

simultaneous
collaboration

19 MV: So that answers somehow question no. 4. But we are talking about two different groups here. The people, as you say, the people who work together, and then there are other people who have slots where they operate and then pass the information onto engineers.

Q4

20 BH: Possibly that is true but I don't have enough experience to know whether that sort of rather traditional way of working is still around. Maybe that is what you have got to find out.

21 MV: But from your own experience you are saying that there is no such a case.

22 BH: Never, never. Not since I left college really. Of all the practices I have worked in, which has mainly been Fosters and my own, they were in there right from the beginning. The two disciplines worked together. Sometimes the architects brought to a discussion something that they had been thinking about but I wouldn't say it was more than that. I wouldn't say they came with a fixed concept and ask the engineers to make it stand up. I would have thought that was pretty unusual. Certainly on Schlumberger which I had a little bit to do with because I know Michael very well, I know that it certainly wasn't the way it worked there. I think the whole concept of the tent providing that sort of work space in the middle of the building, is something that came out of the discussion with engineers. I think there is a problem, I suppose one would have had with the word 'unconventional'. I think I know what you mean. Did you try and define what you meant by unconventional?

architects and engineers work together with no fixed ideas

23 MV: Yes, and certainly in the letter I give a very general definition here, saying that it is about structure covering long span spaces without employing beam column structural systems. But that was in order to include all possible categories. So that I can cover a very wide range of projects.

24 BH: Because in a way theoretically, you can have an unconventional structure with something very small, can't you. There isn't long spans. Could be just a house or a detail, and you recognise that.

unconventionality is irrelevant to the scale of a project

25 MV: I appreciate that.

26 BH: Is this a situation where you started by thinking very generally that you could do buildings with fairly conventional structures but there were going to be situations where that wouldn't do and therefore you would need an unconventional structure and therefore you wanted to find out how those would be designed. Is that how it came about?

27 MV: No, it came about by looking at the educational point of view. I thought that as a conventional architect myself I wouldn't be in a position to design an unconventional structure, the way I looked at it. So I asked myself what has to happen in education so that an engineer is in a position to communicate ideas and architects to then produce something unconventional. And that's what I am asking at question 2 here which talks about the architectural language, and I don't know what you feel about that. But it's maybe talking about the language, the vocabulary of forms and how this advances in design. How much do we need to know? Is it true that there is a different language?

28 BH: I am not sure - there is a sense in which you set out to solve a particular problem. You don't know what the solution is going to be. I'm thinking about this as I go along really, but if you take something like Schlumberger where they had offices around the edge and they wanted quite a wide span, there is obviously quite a lot of different ways of doing that and you don't necessarily have to do it as a tent structure. They could have done it presumably as a simple truss.

ways of
resolving the
same
problem
conventionall
y or
unconvention
ally

So in a sense I don't suppose on the one hand I don't think they set out necessarily by knowing what the solution was going to be, or it is possible that the architects, because they were interested in tents they decided that they wanted to use some sort of tent anyway so it is quite possible, in a way of answering your question, that they actually wanted to do something quite vigorous - they didn't quite know what it was going to look like so in a way that solution was ruled out in the beginning. So I think there is a sense in which, if that is what one of your questions is about, but certain architects might well approach a problem, wanting to show off or to make the problem.....

29 MV: To innovate, to do something different.

30 BH: Yes, possibly to innovate but to give the building a quality which it wouldn't have if you treated it conventionally. I think there probably is a sense in which a lot of the sort of tent structures could be solved in a much simpler way, but wouldn't necessarily give you other qualities that the designers actually want. I often think that about the Munich Stadium. I haven't studied it in detail recently but I do remember thinking that on plan it was a very expensive structure, but it only covered about half the people, didn't it?

unconventional does not always mean functional

31 MV: That's right, yes - If you look at the section here, you see it lifts up and the projection is not sufficient, especially if you have a gale, or a storm, or for the people down here who get the rain.

32 BH: Whereas it would have been quite easy to do - I don't know what - but a really boring structure would have been something like what we see in all the neo-italian football grounds have got great big cantilevered roofs and presumably most people stay in the dry. This is a situation where they very definitely wanted to use this sort of roof. It carried other signals. It gave out other signals. It was a new thing at the time and I suppose a new image for the Olympics. It's quite possible that was the case.

33 MV: But do you think, to get to the question, that the attempt to innovate would influence the process - having worked with Foster to begin with now that you are involved in a more conventional way. Do you think that the process then was different to what you are doing today.

34 BH: I think it probably is, yes I think certainly when I was there we would get things made which hadn't been made before. Or we would undertake tests that I wouldn't ever think of doing here.

importance
of tests when
design
unconvention-
ally

35 MV: Tests for what?

36 BH: Well, different sorts of structures, or different materials. I'm trying to think of an example.

37 MV: Physical modelling?

38 BH: Yes, but also making - there was a big tradition for making four side pieces for actually making joints. So I think yes, that the desire to do those sorts of structures did influence the process - and we had to have people around who could respond. There is a building that we did call the Sainsbury Centre which you probably know in Norwich, which has got a big span and it has a truss that goes all the way around. But this had metal panels on the outside and it had a very complicated gasket detail. I think the structure was less complicated but certainly there was an enormous amount of work went on having different panels made and testing them in different parts of the world. On the Hong-Kong Bank there were enormous numbers of alternatives to the glass wall assemblies and they were all tested in wind tunnels with ranges and all that sort of thing, and the feedback from that changed the design.

39 MV: How did you change it?

40 BH: Well, if the water came in you would make a change. You would redesign something to try and keep the water out. OK rather simplistic. But if you design something that looks like that and then you tested it and then tried that and that didn't work, and then you tried that you often finished up with that. But you went through a process of research and development and evolution, which I don't think we do quite so much here. I think on the Sainsbury Centre, to go back to that, I think there were a number of different structures tried out.

how
unconvention
ality
influenced
the process

Let me just get the book and I'll show you. You see this was a solid steel web scheme, and those are Tony Hunt's sketches which he did at a meeting like this roughly and then I think he drew them up in a slightly more neat fashion for this book. But I think those are certainly things which in discussion we would talk about how these struts would be fixed to the beams and so on. You see there are different methods of doing it there. There is another one there which is more or less what we finished up with, which was an open. The desire to do it as an open truss -

41 MV: To incorporate services perhaps.

42 BH: Yes exactly and walkways so that you could actually walk across there.

43 BH: Now that was a process - that development from there to there - with other steps in between, came about as a result of sitting around the table and talking with engineers and with people who made these panels. We had these fancy panels made which actually in the end didn't work.

simultaneous
involvement

44 MV: Is this something for which Sir Norman has been sued?

45 BH: No the client just paid to have them all replaced. Which is very lucky for him.

46 BH: You see the same panel system goes right over the roof and down the other

47 BH: side and this is nearly flat. It has a very slight chamber on it - so the whole thing is quite unconventional. But I don't think it involved a particularly hard to imagine process of design. It was just done around the table and then people went off and tried different things. A lot of testing was done of panels and sub-contractors made up. We had quite a lot of differences of panels made.

Here we are - this guy was from a firm - these are vacuum formed - they made them up on wooden rolls at first - that's not how the final ones were made - but you see look at all these gaskets laid out on the roof and it is fantastically complicated and the chances of it leaking are quite high - in fact I don't think it actually leaked - what happened in the end is that these panels which were filled with foam, and they had a back piece to them, they actually started to delaminate after four or five years. The foam started to come away from the metal.

48 MV: I think that perhaps answers no. 8 - doesn't it?

49 BH: Well it depends by what you mean by "an early stage" - I think if we take this as an example, I think what happens is that to begin with, everyone thought it was going to be done as either a pin jointed beam and column system and let's say we had been working on it for two or three months, when that scheme was still around, I don't think at that stage anyone had a clear idea of what was going to go on the outside. Maybe Norman did, I don't know, but we actually hadn't got that far. It was only after about another six months that these panels and so forth were being made.

50 MV: So that is not necessarily true.

51 BH: No, I think in my own experience, both there and here is that you set out on a course and you try out maybe two or three options - and then maybe those two get eliminated and you take the main one and you go developing that and then you try out different materials in relation to that. It's a sort of linear process really.

linear
process

52 MV: It could lead us to question no. 5. Because it refers to specific knowledge of technical and other issues. But do you think that that is a further difficulty in the design process, when one designs unconventional structures?

53 BH: Well, I think if you design unconventional structures you have to perhaps be aware that it might take longer and it might take more people - you have to get other people involved, or no - it's one of the two - you either take longer yourself finding things out or you have to get other people involved in order to test things that you don't know in a conventional way how they are going to behave. This is certainly true of tent structures in the early days. They couldn't calculate it - as I understand it - so they had to test things and see. So the experience is built up empirically.

designing
unconvention
al structures
might take
longer or
require more
people
experience is
built up
empirically

With the Foster experience, to push on to do something that might have been considered unconventional, involved a sort of network of other people, all working in relation to the development of the design. Maybe two or three engineers, group of architects and a couple of technical people. With the Sainsbury Centre it was the first time we had done that really. I think having done it once you then found out all sorts of things which you used in your own experience next time.

54 BH: The Willis Faber building, which was that glass walled building, you probably know it, you know the one which has nothing else but glass.

55 MV: In the same place, is it?

56 BH: No it's actually in Ipswich, it has nothing else but glass on the outside which you probably will remember. We knew it would work but it took a long while getting all the details worked out and being sure and we had to involve Pilkingtons and we had to get them to take some of the responsibility. Because the other thing that comes into all this ...

57 MV: Did the contractor take responsibility eventually?

58 BH: The glass supplier - because he erected the glass wall, Pilkingtons. We worked with Pilkingtons, but in the end, I think what happened was we had to persuade them to take it on for them to do it and for them to assume responsibility for it and this business of responsibilities is very important because if this failed the money involved would be enormous.

responsibility
taken by the
glass
manufacturer

59 MV: And your reputation of course.

60 BH: Insurance and all that sort of thing - you don't take on more than you can cope with financially. We have insurance of £1.000.000 and most people do now. That's a bigger issue - if that glass wall fell down I don't know

risk taking

61 BH: It has been brilliant, there has been no problem with the design, but that was quite a big first and again Pilkingtons did a lot of tests, they built several pieces of this and siliconed the joints and they tested it under hot and cold, firing water at it and so on. But it was done as a holistic process with engineers, architects and other members of the design team watching to see what happened.

62 MV: You said it's linear, but it's actually cyclic - isn't it? There is some iteration there going on.

63 BH: I suppose maybe, I am not sure - maybe it is cyclic in some senses but I always felt that to begin with, certainly at Fosters, one looked at several options, several ways of doing things and then maybe that narrowed down to just (a) and (c) and that narrowed down to (c) and each time you narrowed down you carried out checks and you were building models and you were maybe getting real mock ups made and that why we went forward with the (c) because you had eliminated the others for all those reasons. You didn't like the way it looked, or it didn't behave properly or it was too expensive.

64 MV: I think we seem to have covered 9 and 10 already. You talked about people's mistakes and previous experience - 9 asks how significant it is for the process of learning from other people's mistakes and previous experience? You did talk about the empirical approach.

65 BH: I think that it is self evident, I think that is obviously important and I if you think you are going to be involved in an unconventional structure, you clearly want to try and use experts who have been there before if you can. That is why people go to Arups and to Tony Hunt's office and so on, they have a lot of experience in some types of unconventional structure. But I suppose my position is that I think in our practice we do quite a lot of unconventional things but they don't look it. The things you have been talking about are things that are overtly experimental. They look different.

use of
experts
design
unconvention
ally and
modestly

66 MV: You talked about the stressful situation a design scheme can be in, which perhaps reflects the determination and commitment that No. 10 is asking here, but how do you relate that to innovation -if you can speak about it a bit more.

67 BH: Oh, I'm sure. I think if you are going to try and do something that hasn't been done before, it is going to involve a lot more time and effort and worry. If you want a quiet life you don't try and innovate. You just play safe. It's quite interesting - there is a firm in London, an architectural firm, but they have actually cornered the market in dealing with building failures. Where for various reasons the original partners were all interested in building technology and they were less interested in designing things and I think as a result of this they started to get known as a firm that would put right things that had gone wrong. They were trouble shooters. You ought to go and see them - they are quite interesting. They are somewhere in North London.

something
new requires
much longer
time
failures occur
mostly with
conventional
structures!

68 MV: How do you manage the people of your generation of architects having the same handwriting?

69 BH: You don't get into architecture school unless you've got it.

70 MV: Look at this.

71 BH: That's Adie's isn't it.? Well he copied me.

72 BH: The point about that story is that what I wanted to tell you about those people is that we spoke to them about a year or so ago because we had a problem with something and the interesting thing was that the things that went wrong on the whole were not the innovative designs, they were conventional designs.

73 MV: Really!

74 BH: Yes. 80% of their work was just bog standard building technology where people had not put the DPC in the right place or they had got condensation - they very rarely had problems with high tech. Which is quite interesting. So if you wanted to follow up that side of it I could get you a name there - you ought to go and see them. I think question 10 is self evident . Nobody's going to say that it doesn't require any hard work, because it clearly does because you have got to do all these extra

Q10

75 MV: It's risk taking, isn't it - at the end of the day it is a risk taking process.

76 BH: Yes, and that is why in the Sainsbury's Centre, despite all the effort that went into it, all the panels failed - nobody knew they were going to fail and everything was done to try and guarantee that nothing would go wrong, but on Schlumberger, as far as I know, everything has been fine. But then I think that it is a much less complicated technical answer, you know it's just a glass skin and the silicone technology had got to the point where it was capable of just being applied in this way and it didn't fail and even if it does fail, after 20 years, it is quite easy to cut it up, because as the glass panels as you probably can guess are full size, each one is held in place so that you can cut out the silicone and re-silicone it without having to change the windows on it. If glass gets broken you can take one panel out and put another panel in quite easily. Everyone is doing it now - lots of glass wall assemblies based on that idea.

77 MV: So it seems to be a debate about what is innovative and what becomes

78 BH: I'm tending to support your thesis really, I think. I supposed if I was pressed I think there is a situation where people set out to do things. I certainly think Norman sets out to do single bits on how to do things that were different from what we put down before. Because he wanted to. I don't think he necessarily knew what it was going to be but he might intuitively, when he embarked upon that building, had some sort of idea. I don't know if it is in this book actually.....I'm just looking for one of his early sketches.....This is a typical (a) and (b) - he said, this is a note to somebody who was on our team, Martin Francis - "could you please draw up both options for Wednesday's Pilkingtons' meeting - Norman." What he saw there is that you could take a

people set
out to design
and try new
things out

79 BH: flashing over the top and fix it through to the glass, but better still would be to take the glass up and then have a strap that run along and then fix through, like that So you allow the glass to go right up to the top and you had a very small flashing. Now that is a case of the architect, the designer, driving the rest of the team.

The subcontractors - Pilkingtons. The glass technology guy who was working in our office, Martin Francis, and probably the engineers in order to pursue a visual idea, so I think that is a very good example of something that if you have a brilliant designer, which Norman is, they push for a certain way of trying to do something, both those ideas would be fine but obviously that is a more innovative idea - it's a more unconventional idea. This a more conventional where you just take the flashing over the top and you just cover the top of the glass. But you see this is how it finished up being, you have these straps which allow the glass to be very thin right up to the top of the building.

80 MV: You talked earlier about physical modelling used. Does this answer no. 7?

81 BH: Yes.

82 MV: which talks about the means of communication and simulation. It asks how does the different degree of familiarity that individuals have with means of communication and simulation affect the process itself.

83 MV: Just to give you a clue as to what I mean by familiarity with means of communication and simulation, it is about explaining to the group or the client. The three dimensional qualities of the concept and of course the other purpose itself is simulation to see how a structure behaves. I don't know whether you feel that Norman, for example, would need that, because it refers to a degree of familiarity that individuals have with means of communication. How does the different degree of familiarity affect the process?

84 BH: Well, I am not quite sure what the question means but I think it's certainly at Fosters it was true that having been in a tradition in the office of making models, if models is one of the things one is talking about, it certainly helped to progress the design. How does the different degree of familiarity effect the process? I think it made it better. You can see the ones I showed you of the

85 BH: Sainsbury's Centre - this is only a few of them. This is a model, that's a model. That's a mock-up, that's the real thing. They all help enormously, so I think the work was done in an environment where these things were regarded as normal. Drawings too. These drawings that Tony Hunt did - these are all models - I made most of that model, those are my sculptures of people. We did those drawings in the office to show how the structure went together. Those are Norman's drawings which he filled book after book with.

use of
models

86 MV: How do you do things in a conventional practice such as this one?.

87 BH: Exactly the same.

exactly the
same

88 MV: So it's no different.

89 BH: You can see them around, we just build lots of models. We had a meeting yesterday with that model there. It is not a structural model, but it is a design model.

90 MV: Was it to talk to the client?

91 BH: Yes it was - it's a very crude model, but he understands it. This is a competition, we weren't asked to do the model but we built it anyway to show

92 BH: it's for a theatre in a School in Hammersmith - we won the competition largely I think because we made those models. It means you can actually see what's inside and how an idea actually works. And you can see a big atrium here so that they can display pictures from the art department. All that sort of thing is so much easier, particularly for people who cannot read drawings. So the tradition goes on. I think all the people who worked at Fosters are now lots of smaller firms. This is standard stuff and Sam Price who you are seeing later on this morning would expect us to do something like that. He would feel it quite normal and it helps to progress the design process much quicker than if you are working in isolation.

93 MV: Is it more important for unconventional structures to visualise with modelling.

94 BH: Probably. I don't know if you saw there was a very good exhibition at the RIBA recently on bridges. There were six designs for bridges - it was a bridge competition for the Royal Docks and it was won by Ian Ritchie. That was very interesting because there were one to six solutions. There were some suspension structures and there were truss structures. Ian did a very strange scheme which in fact Sam was the engineer for, so you can ask him about that. It was a very interesting situation with all solving the same problem. All the solutions were quite different and certainly the two that won, certainly one could see why they had won. They were very elegant and seemed to use the minimum of materials, but they were all produced from team groups - Arups, Whitby and Bird.

95 MV: So that perhaps answers no. 3.

96 BH: 4. I think it is probably self evident. If you are trying to do something that you haven't done before - it is going to take longer, isn't it?

97 MV: I think you answered that earlier, you said that you don't remember any traditional practice the way that the question implies.

98 BH: But there probably are some I just don't think you will find any because Adie will put you in touch with people like me so you will tend to get people who are used to working in groups with cross disciplines. I imagine there are still some firms and traditionally one had this image of the architect designing something and the engineer making it stand up. I don't know if that still goes on. It seems amazing if it does - but it probably does. So the answer is definitely yes for question 4.

99 BH: 5. Is the lack of specific knowledge of technical and other issues a further difficulty of the design process of unconventional structures?

100 BH: Well again I think that's obvious, I think to do something like the Munich stadium is very complicated and you need a mixture of experience and technical skill and you need to know where to get the technical skill if you haven't got it yourself.

something
complicated
requires
experience
and technical
skills

101 MV: Does it answer no. 3, do you think partly?

102 BH: Yes it is definitely true. You can't do it on your own.

103 MV: But the question asks whether there is a stronger interrelation and independence of architectural and engineering considerations...

104 BH: Well, it is saying the same thing. I think what I am agreeing with you is that there has to be a stronger interrelation and interdependence, otherwise you can't do it because you are setting out to do something you don't know what the answer is. You don't know what it's going to finish up being like. Even if you know broadly speaking it's going to be tent, you don't know exactly how it's going to be made and you know what the details are going to be and what the problems are going to be. If you take the Lords cricket ground tent where it stands on six posts, well that is an amazing achievement if it's to do with being connected so the posts didn't get in the way.

stronger
interrelation
and
intrepende
nce of
architectural
and
engineering
work

105 MV: Just a series of connected umbrellas that's going around. You can be very cynical about it and say at the end of the day it's not such an achievement.

106 BH: But when you go and see it, it looks quite impressive.

107 MV: Yes it does. So that can lead us actually to no. 1 - and that is quite quite important here - whether you think that this interrelation and interdependence influences the process.

108 BH: Well I think now that we have talked it through, I think it obviously does, doesn't it?

109 MV: I hope I haven't influenced your thinking.

110 BH: No, I don't think so. I think all I am saying is that I think I don't necessarily

111 BH: I know what you mean by unconventional structures but I think really there is just structure and I think some of them turn out to be unconventional. You don't know that is what is going to be and as I said to you about 20 minutes ago, we have designed some quite unconventional things but you wouldn't really know it by looking at them and we have worked in the same way as we would if we were designing something that you knew that was going to be fairly unconventional.

some
structures
turn out to be
unconvention
al

112 MV: So there are pompously unconventional people and modest ones?

113 BH: Well, it depends what sort of work you are doing. We tend for various reasons to feel like making a big song and dance of structure although we are very interested in structure but rather in the same way that one or two other people are. I think Michael Hopkins is very interested in the way structure works. We haven't had the sort of work where you needed to do very wide spans but if we did I think I wouldn't be afraid of doing something unconventional.

114 MV: So you see the reason for the distinction now that you are talking about it because I understand what you say about people's reservations in the case of convention - that is my argument, that the reason we don't really know how according to the evolution process of design we get from (a) to (b) but sometimes the idea becomes more unconventional. and therefore we can't explain how from a conventional idea an unconventional emerged. So by looking At something we can say that it seems rather strange, that is to say unusual.

115 BH: I suppose I am a bit cynical I think that certain strange structures are there because people wanted to do strange structures.

unconventional as an end in itself

116 MV: Yes, I understand that, I think I agree with that.

117 BH: I think part of the brief for the Munich Stadium was to do something that would be eye catching possibly.

118 MV: And as you say for all the experts, people have exactly the same idea.

119 BH: Nobody want a sensible pavilion. When Michael set out to do Lords and the Schlumberger job he needed to surround himself with good people, people who got experience in that field which they have.

good people

120 MV: I talked to John Pringle about this.

121 BH: And he supports that view, does he?

122 MV: Yes. So we are left with two questions.

123 BH: 12. Do you think that current educational practice equips architects and engineers to work together?

124 BH: I don't really know the answer to that, I think it's probably getting better. I have done a lot of teaching in the past but I haven't really been teaching much recently, so I don't really know. I mean Sam teaches at Cambridge and he can tell you what he thinks. I would like to think they are taught to work together but I don't know in practice whether that's happening. I mean what is your feeling about that?

125 MV: Well I think it depends on the School really. There are two different schools of thought that support the idea. I think that the Bath School of thought is that architects and engineers have to get together from year 1 and work. I think Cambridge has a different view that is why they established this masters in the interdisciplinary course for architects, engineers, environmental engineers and others. So I think both Schools which have a good reputation believe that there has to be some sort of concurrent education but I think the issue they disagree on is when should that take place. I am not quite sure that people like you had this co-education.

126 BH: No, not at all.

127 MV: Which obviously means that is sometimes the reason there is a problem in people working together but that can also be attributed to personalities. Whether one wants to be the prima donna of the design team Or how one can come to terms with the fact that someone else can come up with more interesting ideas than oneself. I do believe that it doesn't have to do necessarily with education but I don't believe that either Bath or Cambridge projects are easy to teach.

128 BH: My feeling is that an awful lot of practices are quite comfortable working with engineers right from the beginning. That is my gut feeling, because otherwise you wouldn't get the sort of results that you do get now. There is a tremendous compatibility.

We went to Waterloo station, the new one by Nick Grimshaw this weekend because we went on the Eurostar. Just looking at all the details. The way the tiny little brackets and joints and all sorts of things going on - that is quite a busy building structurally but you can't resolve all those things without working very closely with engineers. All those middle generation practices must do in order to get the thing looking right in the end. You can't do it any other way - you have to sit down and do it together. So I think quite a lot of students who haven't had that experience at school because it is quite difficult to simulate it find out pretty quickly in practice.

129 MV: I think this leads to question 13.

130 BH: 13. Is the borderline between the skills and roles of architects and those of engineers appropriate for the design of unconventional structures?

131 BH: Which borderline is it?

132 MV: Do you think there is one to start with?

133 BH: Not particularly. I think good architects are also engineers and good engineers are also good architects. Sam Price is a brilliant architect. Don't tell him, but he is a very good designer and a very good engineer. I think the best people move across boundaries. I don't think you'll get somebody who says I am not going to comment on that because I am not an architect.

I mean they might be rather hesitant about saying something but on the whole there is a lot of cross fertilisation between good engineers and good architects. I have never been to a meeting where somebody said you can't say that because you are only an engineer. We don't work with those sorts of engineers.

134 MV: I am really glad to see that people agree with me at the end of the day. But as you say I think there is probably a more philosophical question here about the definition of the term to start with.

135 BH: I think so, maybe that is what one could be having a problem with.

136 MV: Yes.

137 BH: And what do you think about that yourself now.

138 MV: Well, partly because I worked very closely with Buro Happold and I think they somehow injected me with their enthusiasm and their....

139 BH: Right.

best people
move across
boundaries

140 MV: I find talking to people like Happold that it has been in the culture of the office. In the same way that Michael Dickson, he is very knowledgeable, when it comes to architecture, he is a ver knowledgable engineer. .

So it is quite confusing for the thesis itself because you don't have an objective view point. You are too close to it to be objective. So this is one of the reasons why the thesis, is not exactly a narrow minded approach, but I saw unconventional structures as something very different from what I used to know and it is true that technically speaking I learned quite a lot. Because I was working full time in the past as a post graduate student and at the same time I had the big go ahead to attend meetings and see how people did models. I did some models myself to get closer to the real thing I think that in a way influenced the whole idea of the thesis.

141 BH: I suppose I have the greatest difficulty with the words conventional and unconventional. I think really there is just structure and some structures. We have discussed it, haven't we? In things that don't look particularly unconventional - there is a lot of work that goes into things which are quite clever and quite interesting in a much less overt way, so I think I would say there is just structure, but I would agree that in some cases there is a desire to do something more with structure than just solve it the simplest possible way.

146 MV: And it was at the time when things happened which has to do with the title here, the unconventional, and again there is a debate in the thesis about what you mean by the term unconventional and when and where you define that - and then it refers to the culture of nomads and the Arabs and how they accept tent structures.

Interview with Robin Snell

1 MV: I think that the commitment here was meant to cover all the different categories that could be under the general umbrella of the conventional structures. That was in order to study the process. I gave a very general and broad terms to the word unconventional so that I can cover all the different categories.

2 RS: Are they basically large structures which span large areas? Is that your definition? It is not necessarily the technology involved in that, it is actually the nature of the space and enclosures.

3 MV: The form of the building

4 RS: Yes, but what comes first isn't the form of the building, what comes first is the purpose of the structure, which is to enclose a large open space.

5 MV: Well that starts answering question no. 2 somehow. You have designed unconventional structures yourself.

6 RS: I'll go through your questions one by one.

Q1

7 RS: To answer the first question I think that the design process always comes from the purpose of the project. It doesn't come from the fact that you might want to do an unconventional structure. So, I think of the question actually the reverse is true: unconventional structures come from the brief. It is the brief that influences the design; this then translates into an unconventional structure.

8 MV: Do you think that the process is different in that case. Are there different things happening during the process when the brief somehow can be met by employing an unconventional structure?

9 RS: Well, I think by nature, most of the building examples that you have given, they are enclosing very large open spaces whether it be Jeddah or Schlumberger and so forth and those buildings have come from the nature of the purpose

10 RS: For instance in Schlumberger the purpose was to span 22 metres and to create a volume that was 22 metres wide by 20 metres high by 60 metres long and the logic of using fabric was to create that span and form that space in an economical and efficient way. That made an unconventional structure. We didn't start out by saying we must design an unconventional structure. We started out by looking at the brief.

unconventional as an answer to the brief

11 MV: But surely there are more conventional solutions to the problems, aren't there? I mean in the Schlumberger case it could be a very long truss system to cover the long span between spaces

12 RS: Yes there is, but I think the change happens when one decides to use a particular material. The earliest schemes didn't have fabric they had materials such as glass -but to do the most economic way of actually covering that space was to use a fabric.

relationship between material and adopted form

Q8

13 MV: Do you want to relate that to question no. 8

14 MV: No. 8 - Is it important that construction details and choice of materials have to be resolved at an early stage?

15 RS: Yes, I think is in some ways obviously influences the design and the major of the structure and in Schlumberger's case we chose to use fabric because (a) it was economic and it involved potentially less materials in terms of the support structure than if it had been glazing and (b) also the maintenance was less. So all those factors were involved in the decision. The nature of designing with fabric led to the structure that one sees now.

16 MV: So now we can return to no. 2

Q2

17 MV: Do you think that the architectural language of unconventional forms is different from that for conventional and that influences the process?

18 RS: Yes. I think the architectural language is about more dramatic structures and by virtue of the fact that one is doing a more dramatic thing, in that one's spanning a much larger space with less structure, it is going to be more exceptional.

dramatic
structures to
cover long
spans

19 MV: But do you think that influences the process itself? Are there different things happening during the process, when a dramatic structure is designed?

20 RS: Not really, I think in the design process one can use the same design philosophy whether one is designing a table or a chair to a house. It depends on the approach of a particular designer, I think.

the design
process is the
same

Q3

21 MV: So how do you feel that could answer then question no. 3, because if that is the case there must be, or I am asking whether there is a stronger interrelation or interdependence of architectural and engineering considerations which could then influence the process.

more
involvement
of structural
engineer on a
large roof
structure

22 RS: I think visually there is potentially more involvement of the structural engineer on something like a large span roof structure, but that doesn't necessarily have to be the case. The relationship between architects and the engineer can be just as intense and just as important if one is designing a staircase, so I don't see there is necessarily a difference in my particular approach to design, I think outwardly it looks more 'engineered' because of the nature of the structure itself but for me that is not the case. I think the relationship of an architect and engineer is consistent whether it be designing very large span spaces or very short span spaces.

23 MV: So you have already answered no. 4

Q4

24 RS: Is there a necessity for simultaneous and equal involvement of architects and engineers from day one for unconventional structures? Is this more necessary than for conventional structures?

25 RS: Well it depends. To answer the last part, is it more necessary for conventional structures?- it depends on the particular designer or architect involved, or the particular engineer. I think if one is interested in design then yes there is, but I wouldn't just say that necessity is for unconventional structures.

differences
between
unconvention
al and
conventional
vary.
according to
individuals
perception
and
understandin
g

I must say that I'm not sure of the difference of what you call a conventional structure or unconventional structure, because I think depending on the way one approaches design one can argue that there is very little difference, in my language, of something that is conventional or unconventional. And particularly the relationship of an architect and engineer, I like to think, it is consistent whether it be more traditional or more unconventional.

26 MV: 5. Is the lack of specific knowledge of technical and other issues a further difficulty of the design process of unconventional structures?

Q5

27 RS: Well I think the great thing about the design process, is that I think that it is more to do with the design process than necessarily whether something is conventional or unconventional. I think with any design process the different individuals and people who come into the design scenario, all bring with them different experiences. So for instance an architect has had different experiences with different buildings as has the engineer, and they all bring a different 'baggage' with them.

knowledge
can inhibit
creativity

Very often it is not the architect who comes up with the creative lead to solve something. It could be anybody. But I think the important thing is that anything is possible, so I don't think one should get too hung up on specific technical knowledge of things. When one establishes the principles generally one finds that one can actually research the technology and research the knowledge that one needs to know in order to solve the problem.

28 MV: Could that possibly be related to no. 9

29 MV: 9. How significant is it for the process to learn from other people's mistakes and previous experiences?

Q9

30 RS: Yes, I think that is very important and I can remember Peter Rice saying once that "the most important thing is to learn from your mistakes" and you can learn from previous mistakes. He also said that in structural terms 'if it looks visually right on the drawing it generally is right structurally' I think that's the way I certainly work that you build up a body of knowledge and understanding by what you have covered, what you have designed and what you have been involved in.

learn from
your
mistakes

31 MV: That has already answered no. 6 as well then.

Q6

32 RS: Yes.

33 MV: 7. How does the different degree of familiarity that individuals have with means of communication and simulation affect the process itself?

Q7

34 MV: It could be related to your experience of Schlumberger, then you can think of the physical models you used, the computer programs and what would be different if those means were not available, how they influenced the process. So the question refers to the influence and the different degree of familiarity that individuals have with these means of communication. And how this degree of familiarity affects the process itself. So just think of the design team when you operated on Schlumberger. You can argue that means of communication are physical models or it could be discussions or sketches.

no set of
rules or
principles

35 RS: Well. In some ways if one talks about means of communication that has an awful lot to do with the process itself and the previous question which was about the experience that you take to the project, particularly with fabric structures. There are to a certain degree set rules and set principles that one has to follow, and the invention and the creativity is actually using those rules and pushing them down a different road to suit a specific purpose.

Because of the fabric - OK the technology of fabric does develop and they develop new fabrics and new coatings, but the principles in terms of structural principles are similar and as an architect one actually knows to understand the principles and the technical issues. But obviously one relies on an engineer to be able to calculate them. The calculations are complicated so an architect tends to know the rules or a little of the rules, and uses an engineer to guide those principals.

36 MV: But do you feel that this, as you said the architect doesn't have this familiarity with calculations but does this lack of knowledge if you like influence the process?

design is
about
postulating
as in
scientific
research

37 RS: No, not really, because design is about postulating as in scientific research. It is about making suggestions on drawings and a theory that may or may not be correct, and then demonstrating that technically. The design process is simialr

You create the technology and you create the method for proving things, but you don't start off with all that knowledge, you actually start off with - and I think that creative people probably have less knowledge than more technical based people. One actually has to understand the principles in order to design. You don't have to know all the technical knowledge and in some cases it's a disadvantage to have all the technical knowledge.

38 MV: It is because you

39 RS: You are inhibited. It's the same as anything really if you are an expert technician, who knows all the technology, that can actually bring with it inhibitions that if one doesn't have that knowledge one is slightly more free.

40 RS: You mentioned the Sydney Opera House which is a prime example that was unbuildable in terms of calculations and technology when the competition was won.

41 MV: But it wouldn't have been so innovative if you had all this thinking incorporated

42 RS: The whole essence of that design was Ove Arup and Partners working with Utzon to produce a structure which developed and fitted the form created in the original competition and I think that illustrates the point I was making, that one doesn't actually need to have all the technical knowledge at once. But one needs to know what moves to make and where to go - and that is part of experience.

43 MV: I think is somehow related, because we are talking about naivety, risk taking but they are related to question no. 10.

assembly of
right people

Q10

44 RS: 10. Are commitment, determination and enthusiasm necessary for innovation?

rigour

45 RS: Yes, I think rigour, you missed out a word there, you need to be rigorous about it and you need to work hard and those should be added to that list of key words.

46 MV: Would you like to talk about the risk taking side of innovation, because having experienced the Schlumberger you have probably encountered this issue.

design is a
genuinely
risk taking
process

47 RS: Designing and building any building is a risk, whether it be conventional or unconventional. There are lots of risks - there are financial risks with a client, there are planning risks, there are building regulations risk - and that is part of the process it's part of a journey that you follow to reach the shared goals of the client and the designer so I think what we risk is probably too..... the word is sort of synonymous with the risk of failure which I don't think is particularly applicable.

Certainly to building projects, because I think most building projects at the end of the day need practical, appropriate solutions. Whether they be conventional or whatever unconventional means. I think it is very difficult to separate the two, because one is always taking risks in the design process.

48 MV: So I think no. 11 is a very important question.

Q11

49 RS: 11. Which comes first unconventional structures requiring close collaboration between engineers and architects, or close co-operation between engineers and architects producing unconventional structures?

50 RS: Well it is something lots of people write lots of theses on, the relationship between architects and engineers and I don't think there is any right or wrong way, because it all comes down to the individual and some architects work better with some engineers and some engineers work better with some architects.

engineers
and architects
relationship
comes down
to individuals

51 MV: How is this related to innovation is the question really. Because that answers, I think, no.13. Which is exactly what you said.

Q13

52 RS: I think one has to have a good working relationship and to understand (a) what the architects are trying to strive for because generally the engineer is more technically equipped and (b) the engineer brings as much innovation to a project, certainly in terms of design in my experience, as the architect and I don't think you can separate the two. But as to whether the architect is leading the engineer or the other way round, I don't think that ever applies. I think any successful project is always a team project.

successful
projects are
the outcome
of group
work

53 MV: But what the question is saying is do you think that if an architect and an engineer worked together it is more likely that the outcome of this collaboration is an innovation or an

54 RS: I think there is very little innovation in buildings If one is looking for innovation, one should look to genetics, biochemistry or biology or medicine or - I mean innovation is probably the wrong word. I think there is interesting solutions and there's uplifting designs and bad designs, but there is not much true innovation.

dramatic
structures do
not
necessarily
imply
innovation

For instance Schlumberger was probably the first and largest PTFE roof in the UK, I think. But that is not an innovation by that stage it was quite an old material and certainly the structure of structural steel which isn't particularly innovative. So I think one shouldn't confuse dramatic structures and uplifting structures with innovation.

55 MV: So you are saying that a conventional structure in terms of its appearance and form can add a higher degree of innovation.

56 RS: Possibly, it depends on the project.

57 MV: Well it could be construction detail which is very innovative.

58 RS: The other thing about it is that innovation is tempered by the building process because the building process is a fixed length of time and for true innovation you need a period of development and testing that and particularly in material science which is one area that does affect buildings. There are long testing procedures and testing regimes that one needs to undertake to prove the systems or methods which is generally not available within the constraints of a building project.

innovation is
time
consuming

Again at Schlumberger we designed a large sliding door with very slim extrusions, very high, about 3 metres x 3.6 wide which was the whole facade of the office blocks. Nobody at that time manufactured that as a standard product - been designed for that building it is now a very standard product, but I wouldn't call that innovation. That's just using the components and stretching the boundaries of the engineering capabilities of the material.

59 MV: Is this partly because of your education - did you do a co-educational system with engineers when you were a student and therefore you can't see the difference?

60 RS: Well I think there is a difference. I think that we are different people as a group because we come with different experience and different capabilities - what I am saying is that you can't define the creativity to say the architect is necessarily more creative than an engineer. I think the process is all about the collaboration, not necessarily who is particularly leading that collaboration.

creativity is
irrespective
of
specialization

61 MV: So what do you think of question no. 12 then?

62 RS: 12. Do you think that current educational practice equips architects and engineers to work together?

Q12

63 RS: Well I think education should equip people to work together, whether it be engineers or architects or quantity surveyors and I think one just has to get on with the people involved and to have a good working relationship with them. Whether it be an architect or a builder - I think it is just as important to get on and work together with the people who are actually making the products.

64 MV: But does education serve this?

65 RS: What to educate in social skills? Managing skills? No I don't think it does actually. Probably at a School of Architecture one doesn't learn about these things. The only way one learns that is by actually doing it.

learning by
doing

66 MV: It is also making people aware of the other disciplines' content.

67 RS: You only get that by actually working. You only start to understand relationships between people in the design team by actually doing the job and then it comes down to personalities. I'm not sure you could actually teach it. You can make people aware of the process but until you do it I don't think you really understand it.

68 MV: So you started answering earlier question no. 13

Q13

69 RS: 13. Is the borderline between the skills and roles of architects and those of engineers appropriate for the design of unconventional structures?

70 RS: It is very hard to define that because it depends very much on the architect and the engineer. Some architects do large span structures which are unconventional because they are large spans rely more on the engineer than the architects. The architects in some respect unfortunately are not particularly interested in what the structure looks like. So the answer to that really is it depends on the architect involved I think.

the
borderline
depends on
personalities

But speaking from my experience and my approach I think it important that one is involved in every detail down to the sizing of the screws to the nature of the structure. But some architects are less interested in that. So it really depends on who the lead designer is.

71 MV: Is there such a role of leadership when architects and engineers work together, do you think?

72 RS: Yes one's appointment as an architect generally is as the lead designer unless the original appointment is, for instance Ove Arup & Partners on some projects are appointed as the lead consultant if it is a specifically heavily technically based contract, such as a chemical installation or a research facility and they would then appoint the architect, so in that sense the lead consultant is the engineer. But I would always want to work as the architect as lead consultant.

73 MV: Why is that?

74 RS: Well, because I think the issues and decisions that one takes as an architect, I'm speaking from personal experience now, are different and the priorities are different

75 MV: But do you think that the design processes of unconventional structures is different and more difficult from that of conventional structures?

76 RS: I don't think it is more difficult, I think potentially you could argue that its easier to design what you say are unconventional structures. The Calgary Sports Centre is a large span space. Very often when one has actually solved one design problem the overall problem that one has to solve is quite simple. It is actually spanning x metres in a certain form and when one has got the secret of that design, it is quite simple.

complexities
depend on
the project
and the
purpose

Potentially there are only say half a dozen particular difficult, details or junctions that one needs to solve, whereas if one has a more complex building which is incredibly heavily serviced or very intricately designed it might be a small space, it doesn't need to be large space. So I think the complexities are different depending on the project and the purpose. I think you can actually get slightly confusedMost of these are shapes and forms are, I suppose unconventional. What is the Olympic Ice Stadium in Calgary?

77 MV: It's a saddle-dome. It has a huge ring around. It is quite typical ice stadium or sports centre.

78 RS: Very often one can find that these structures are quite simple in their concept. In Schlumberger in reality it is simple - all one is doing is fixing fabric around the outer edges of a steel frame and then pulling it out with cables, so principally it was very straight forward. The complexity is in actually finding the form, cutting patterns and computer modelling to get the form right and so forth.

But once one has actually solved that and solved the detailing aspects it's quite simple, it's quite straight forward. For me what is important is how all the nuts and bolts and the details go together because I think that is what runs through all these buildings as well being an interesting concept and an interesting idea, that is carried all the way through to the final details of the project.

importance
of detail

79 MV: So I think the point you are making is that the reason for such a distinction between the design processes of (a) and (b).....

80 RS: What I am saying is, and this isn't for all architects, I am saying that for me, whether I am designing a simple, what you would call conventional roof I would still have the same relationship and the same approach to the design as if I were designing something that what you would consider unconventional and it wouldn't effect me at all. I appreciate there is a difference in terms of the complexity of the structure.

For instance Sydney Opera House, but there again these buildings are very much one offs. You could probably call Glyndebourne Opera House an unconventional structure, nowadays, because its a huge building using lime mortar with no expansion, but it's not innovative. It's unconventional. I think one has to be slightly careful about how one uses the word unconventional.

Interview with Sam Price

1 SP: I think the whole issue of unconventional and conventional, was to define unconventional structures as simply long spans, wouldn't be good enough and in fact you might have quite a small scale building which might have a degree of unconventionalism about it. I suppose when you get into long spans you are definitely into what you could call unconventional structures and so it probably does make the point that you are trying to make, but I think that you could also say that sometimes something as small.....

Well for instance, the first thing I can think of, I mean this is not rehearsed I am just thinking now. The first thing I can think of which I would say involves the same sort of effort between architects and engineers were some little castings for handrail posts for an underground station which we did with Alan Brooks Associates, not so long ago, where they wanted something that had this sort of form and then how should that sort of form actually represent the forces that might be in a handrail and how would they be nice to touch and feel and rub against and how do you cast them and which way up and all those sort of things. Which is a sort of complete mixture of architecture and engineering.

Although the crucial issue is not so much engineering because if the architect got it about right that would be perfectly good enough for a handrail, whereas you couldn't get it about right for the Sydney Opera House and it wouldn't be good enough at all so the engineering is not quite such a test, if you see what I mean.

2 MV: Yes

3 SP: I'm making a silly point really. But let's try you first question.

unconvention
al does not
neccesarily
mean big

4 MV: 1. Do you think that the dual architectural and engineering nature of unconventional structures influences the design process itself?

Q1

5 SP: Yes, I do. Because I think if by influencing the design process itself means that the designers have to get much closer together, understand each other, etc. etc. then I think yes, it definitely does.

the designers
have to get
much closer
together

6 MV: Are you saying by that there are cases of designers not needing to get close together when designing a conventional structure, you just said that didn't you?

7 SP: I think actually that there is no case for the architect and engineer not being close together but there are loads of cases where one can get away with it without being close together. But if the architect and the engineer really understood each other and were able to exchange their views. For instance Birkin and the engineer know each other well.

Well I remember a particular instance which shows exactly what I think about that which is that we were talking about some aspect of a building, I can't remember what, which were trying to design, and Birkin said something or another and I said "ummm, well" or something and then somebody else said something and Birkin said "hang on a minute Sam,"... said "ummmm, well what does that mean?" I said "well I am not quite happy with this but actually I think it doesn't matter." So he said "let's talk about it" and we flushed it all out and I don't think it made any difference at all to the course of the conversation, but he felt he wanted to know about that and there are not an awful lot of architects who I work with who really are as thorough and thoughtful as that and it is extremely good and it does mean that you are able to really sort out all sorts of things.

Now my example of the housing association building which has conventional masonry and pre-cast floors. I should think that if the architect knew they were going to do it probably like that they could still make a much better job of it if they got close together and sorted out things - but the things that they wouldn't sort out if they worked far apart from each other are the sort of things which will just cost the clients some thousands of pounds on site and will cause a muddle on site and the contractor will curse a bit and then they will think of a way round it and get on. It is not a crisis.

8 MV: To summarise you are saying that good dynamics of the group is that aspect of the process that can differentiate the design process of unconventional from conventional structures. Is that not so?

9 SP: No, I don't think so. I think I'm saying that in all circumstances I think it would be better if the architect and the engineer work close together. In unconventional structures it's more important, in fact maybe crucial that they do work close together, because I suppose there is more at risk or more....

architects and
engineers
work close
together

10 MV: You see there is another issue here that you didn't mention. You talked about that is why I raise it. You talked about the difference in group dynamics, that people have to work together from day one which automatically perhaps means that there isn't a clear leadership role.

11 SP: I think there is always a leadership role. I am not talking about the risk of something actually going wrong, breaking or whatever, I am talking about the fact that you could go a long way with a design and find that it was wrong and could not be achieved if you weren't working reasonably closely together. I mean I wonder if I can give you a particular example because one of the other sorts of unconventional structures in this sense that you have used, I think, is bridges altogether. Because they are long span and have big loads and all that sort of thing.

Now we recently did a bridge competition with a very interesting architect who had a strong idea of what the bridge should be like before we discussed it at all. It wasn't actually I who discussed it, but one of my partners and so we developed a structure for that bridge, which maybe quite exciting and interesting but isn't the obvious way of creating a bridge. The bridge was costed by a surveyor at four and a half million pounds or something, and it spans about 65 metres and has complications on the end of it - so that's a bridge design. Now in the proceedings of the Institution of Civil Engineers recently there was a very interesting article about a bridge designed by a Czech. engineer, I think, which is a suspension bridge with some pre-stressing and he discussed the whole business of the appearance of the bridge, what would suit the valley, what would look good.

consequence
s when
people work
apart.

In other words he went right into the aesthetics of the thing, explained why he designed this bridge on his own and the bridge is I think, quite an elegant answer, and it cost £750.000 and spans 200 metres. So you see there is a difference there. It spans three times as far and cost a fraction and what I am suggesting is that the first bridge designed in concept by an architect without talking to an engineer that they worked with so we don't understand each other very well, you know, we were not in a position to say this is absolutely not the way to go about designing a bridge and even if we had they would have said well, tough, this is the design - now I think that we can only get ourselves on the whole bad reputations by going on like that here and nobody is going to get any credit out of it.

If it was built people would say it was ridiculous they would also think it a fantastic waste of money and neither the architect or we would get any sense out of it and that is an extreme case. That is what I mean by risk that you just end up with a nonsense.

Q2

12 MV: Do you think that the architectural language of unconventional forms is different from that for conventional and that influences the process?

13 SP: I don't know about the language of unconventional forms.

14 MV: Do you think there is one?

15 SP: I don't think I've defined one, discovered one - no. I think this is all a bit theoretical and philosophical and stuff, but I think that when the architect produces his/her first drawing of this idea, assuming that it is not ...

16 SP:.....masonry and precast plan housing association job but something which is unusual, which might be one of those things that you have chosen, or smaller, as I have said - that the engineer, knowing the architect well, ought to think what is in her mind when she drew the thing? Does she want exactly that or is she, in the drawing of it, interpreting some feelings in herself, which is what I think.

Because I think if you probe at that point and say, but why doubt this, could it be like that? You will discover that what has been drawn is itself an interpretation, so to speak, of a thought and it has had to come out in a particular way because that is the way it has come out, but there may be other ways, it is not necessarily specific. Now what I mean by this is that inherently in a really good piece of architecture, whether it is big or small, is a strong idea of form of some sort or other, of a sense of a building.

17 SP: It maybe organised or disorganised, there is a whole coherence about the thing, which has to be sorted out and it's ideally sorted out by an architect and engineer who understand each other really well and can sort of push against each other. The engineer doesn't necessarily have to be a complete toady to the architect, totally polite, but a certain amount of friction is sometimes quite good, but I think by that sort of exploration from different view points you can sometimes find out all sorts of things about the design and then develop it and you have to have in your mind what the purpose of it is. I don't mean is it going to sell fish and chips or not, but what is the whole idea of this thing.

And of course if it is a housing association thing you probably can't get very far with that because the idea isn't terrifically exciting in architectural terms, I mean you are talking about accommodation at the most economical price and all that sort of stuff.

This is a sales pitch. Have you come across a new magazine call ARQ which has just come out. Well I'll give you a copy because I am on the editorial board of it and it has just come out and I don't know quite what it is going to achieve but I think it is quite different. It is quite different from all the existing architectural magazines. It is published by E Map who publish AJ and AR and New Civil Engineer of course.

Well in there is an article by Gavin Hogben who I have been teaching with at Cambridge in the Diploma Year and he runs that year and he has written a long article about a little pool house which he designed for someone which is just a room really on a lovely site in the country overlooking a hill by a 12 metre swimming pool so they can go in and do lengths so they can open the side up which is on the terrace and sunbathe and so on. So it is a very simple thing and the resulting building that he has produced is not very simple. It is quite simple you might say in basic construction, it hasn't got any sky hooks and funny business, no tents, nothing, it's all made out of quite standard ways of making things.

But the actual idea, the shape and the organisation of windows and where they go and why is actually very much thought about and I think, if I have understood him rightly is slightly deliberately not what you expect, it is partly to do with the business that if you are swimming lengths, back and forth it is as boring as hell really and if you have different views to look at and different things to think about as you go back and forth and the building is constantly moving past.

All that is to do very much with what is the nature of this thing that we are trying to create. It is quite an interesting article I think. I am going to read it at least once more before I understand quite what he is talking about, although I know Gavin quite well really. So I think that coming back to the architectural language of unconventional forms, you have to for each piece of serious architecture which might be say different from building if you want to define the difference between the two, you need to develop the language for the particular thing - I think that is what I am saying. I am not quite sure that answers the question so you will have to find out what is the nature of the thing and then you think we are going to do it with this and with that and do it in such and such a way and so on.

18 MV: So that gives somehow an answer to the second part which refers to the influences that this different architectural language could have on the process. So we are saying basically that the process is the same.

19 SP: I think I am trying to say, I don't think I am really finding fault with your unconventional. I think your definition of unconventional by these particular big buildings is quite neat because it clarifies it quickly and I am trying to unclarify and make it muddier again.

20 MV: You are not the only one!

21 SP: By saying that in a way any really serious piece of architecture which is thoroughly carefully thought about doesn't necessarily have unconventional forms but might have. You see Gavin's pool house is sort of.... I don't know whether it has unconventional form, it might be unconventional in its little building, small scales. That does influence the process.

22 MV: How do you think it would do that?

23 SP: Whether it inherently influences the process or whether you have to have the close co-operation and understanding between people in order to achieve success, that is really what I mean. I think in the case of Gavin's pool house he could probably do that without any particularly close relationship with the engineer. It wouldn't be very difficult because the span is small - perhaps you are right actually. But it is only because the particular materials and form of construction and things of that pool house turn out to be reasonably straight forward although the building itself, I would say is not all that conventional.

It is very interesting actually because besides these long span things, there is another field in building structures which is completely inadequately exploited, I think and that is reinforced concrete. We tend, because engineers are very, very badly taught and we tend to think of things as being putting columns up and beams between the columns and things span onto things so you have a steel work then you have a floor that spans onto the steel and then the steel span but in reinforced concrete that is not right. It's a homogeneous material it can span in all directions at once and all those things like I imagine, I don't know them very well, but I imagine Corbusier's villas between wharfs, with curves and little round columns in sort of almost random places and things are exploiting the properties of reinforced concrete.

24 MV: Felix Candela does that.

25 SP: Yes Candela does that but he does it much more in an engineering way, doesn't he? There very straight and actually it is not so random is it, although I think it is more geometric.

26 MV: Perhaps Calatrava is another example?

27 SP: Yes, he might be but that's sort of extreme. I mean the actual properties of concrete which allow a flat plate of concrete to be supported in a very random way on columns doesn't seem to me to be used at all thoroughly yet.

28 SP: and it does need close co-operation between the engineer and the architect and the actual construction, the way that you actually make the concrete, could be, ought to be, very straight forward. The contractor just puts up some shutters and makes concrete and it is flat, but where the columns go is quite an interesting question between the architect and the engineer and it is not just a specific thing. I mean I was just thinking about the TUC building down the road here, which has some wonderful curvy sides and things and I imagine needed some fairly close co-operation between Arups and I can't remember who designed it.

results of
close
cooperation

So I was trying to answer my own point that Gavin's building built out of conventional materials probably doesn't need close co-operation but I don't think it is really..... If you could say that flat slabs with curvy edges and randomly based columns is unconventional which you could say, then that would equally involve close co-operation. I wonder for instance how closely Fosters and Tony Hunt on the Willis Faber and Dumas building in Ipswich - do you know it - the curvy building. Which has got a wonderful use of concrete slabs and a fairly random feeling about its edge and the way of dealing with this curvy edge. And a very elegant concrete slimming out at the edge of the thing and so on and that is all.....

29 SP: There is a lot of very very good engineering in fact much more interesting actually, getting onto a hobby horse, than for instance Waterloo station, the new international terminal, which doesn't seem to me to be very interesting engineering. You feel looking at it that there is a hell of a lot more steel than there ought to be - probably not more than there needs to be, because I am sure Tony Hunt's got that right, but more than there ought to be to get from here to there with an arched roof between the two. I mean in fact much of a comparison between the amount of steel in that and the amount of steel in Brunel's Paddington station. I think it would be very interesting to see that written up sometime. So anyhow. I think we ought to go on.

Q3

30 MV: 3. Is there a stronger interrelation and interdependence of architectural and engineering considerations when unconventional structures are designed?

31 SP: Well yes - I mean that is just straight isn't it? It needs to be, it should be.

Q4

32 MV: 4. Is there a necessity for simultaneous and equal involvement of architects and engineers from day one for unconventional structures? Is this more necessary than for conventional structures?

33 SP: Yes.

34 MV: I think you have covered that.

35 SP: Yes, yes absolutely.

Q5

36 MV: 5. Is the lack of specific knowledge of technical and other issues a further difficulty of the design process of unconventional structures?

37 SP: Well I think it is, I mean if the lack of the specific knowledge involves everyone in the team which it could do of course the architect would say "how about doing this?" and the engineer would say "crikey I don't know whether that has been done before, whether we could do it" that would be a difficulty. I wonder if that has happened with us? I am sure it has actually and probably. Yes I think it is - let's stick to the question behind your questions, the one you said that people were firing at you saying yes, but this is also true of conventional structures.

lack of
specific
knowledge
can be a
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the design of
quite
conventional
structures

I think in the case of an unconventional structure, of the sort that you have described, if you are going right to the limit of what's known and so on then it could be a further difficulty but it can also be a lack of specific knowledge. Maybe this is silly actually - but the lack of specific knowledge can be a difficulty in the design of quite conventional structures too. If you just don't happen to have the right knowledge.

38 MV: But isn't this a bit contradictory? Because once it is known then it is conventional it is more than likely that all the things you do unconventionally are therefore known?

39 SP: Well, what I am really saying is that because your question made me think have we had difficulty in the design of unconventional structures due to a lack of specific knowledge, and I think we haven't known this specific knowledge which is relevant to the particular unconventional structure without doing some research and finding out about it but there have been other people, Arups or somewhere or other, who did have the specific knowledge, so then it is the particular engineer if you see what I mean.

40 MV: Right. It has happened before, namely the Calgary. It was Bobrowski at the beginning and then they had to bring in the Buro Happold engineers.

41 SP: Yes, Yes

42 MV: It is part of my case study, so.....

43 SP: Yes that is right and that is quite a serious thing and it is matter of the whole design and so on. But I started thinking that what I was saying that we in Price and Myers our knowledge might be limited in some fields of unconventional structures so that we would have difficulty with them. And then I thought well why should I admit to a failure of knowledge in Price and Myers, are there other things to be said on this subject? Do you see what I mean? And I thought, yes, there are.

experience in
conventional
and
unconvention
al structures

For instance I discovered some time ago that in Ove Arup & Partners, they are working on an old building, somewhere or another and the chap I was talking to deals with old buildings in Ove Arup & Partners and he was going on quite a long journey to look at this old building because none of the people in the office of Ove Arups near the old building knew anything about old buildings. Now that you see is the same as, in a silly way, is the same sort of thing. That wouldn't happen in Price and Myers because we know a lot about old buildings.

44 MV: It works the other way round.

45 SP: So the lack of specific knowledge of the technical issues of half timbered 16th century houses in Ove Arup & Partners would give them problems which it wouldn't give us. But on the whole, sticking to your point, yes of course if you get to the forefront of things then you really have to start thinking. There is a sideline here which is interesting, I think, which is that I think that when we get towards the limit of our understanding of things we tend to become much more conservative.

I think that the structure which holds up some of the fabric roofs that have been produced recently looks as if it is heavier than it needs to be and this is because the nearer you get to an unknown of exactly how the wind moves over a fabric roof and what the forces are and whether it is really going to snow that hard and all that sort of thing, the more you rely on computers and things.

Now if as an engineer you are dealing with, well say something easy like, an alteration to Victorian house; somebody says I want to make a hole in this wall here. - you have two ways of knowing about the size of the beam. One is to do a lot of sums and find the size that way and the other way is to look at it and think how anyone would have thought 200 years ago, well last time I used a so and so and this is slightly bigger so I'll use a slightly bigger bit of wood or whatever, you would rely entirely on your experience and in the case of alterations to Victorian houses, if you have done lots of them, you can look at them and think that ought to be such and such and such in steel.

empirical and
scientific
method

lack of
confidence to
rely upon
when
designing a
tent

Then you do the sums and you get a different answer - bigger - then you look both at your original guess and at the size of steel and at the calculations and think which is right and which is wrong and you think, I'm sure it should be smaller than I have worked out and you look at the sums and think well that was a bit conservative and there isn't quite all that weight there and so on and you may actually be able to get the sums to agree with your original guess. Now what I am saying is that you have two ways of assessing something and particularly it would happen with the young engineer and an old engineer in our office. That the young engineer will do the sums and calculate the size and the old engineer will say 'no, you can get away with smaller than that and it really needs to be smaller than that'. Everyone will mind, let's go for it. Then together you go for it and it gets smaller.

Now if you are doing a fantastic tent you have none of that, oh, I'm sure we can get away with something smaller. You have to follow the sums. So when you are going to use a new material and you calculate how much it is going to lengthen the temperature changes or something, which you have never done in a calculation in a conventional building because you know that if the building is that long it is not going to have any particular problems. Because if we did the sums on the conventional building and did find it was going to expand 2 inches - well it doesn't expand 2 inches because if it did it would cause trouble so you see what I mean.

When you have got this new material... somebody said to me recently I would like to do this footbridge with kevlar ropes. I don't know kevlar and I asked one of our engineers, he is a great sailor, he knows absolutely everything about kevlar because of his sailing. So we compared notes about Young's modulus and thermal expansion, all these sort of things and because it was unconventional, as far as I was concerned and probably as far as most engineers are concerned I had to take off all these different things and it would have given me trouble and if it was being used in an unconventional way I would really have to think hard about it so..... and then of course I would have to do all that before I could say to the architect I think what you are asking is a bit too difficult. So that would actually create a difficulty and it does create a difficulty when that sort of thing happens.

If the architect and engineer are trying to work closely together and the engineer says I will have to go away for a fortnight to do the sums it really upsets the whole thing. The communication has to be instant. One of the original partners with Ove Arup once said "an engineer is somebody who can sit down with an architect and size everything without using a slide rule, a calculator or whatever it is, and that is absolutely right. You don't need to do the sums. The sizes may not be quite right but you get the principles. And if you have to go away to do a lot of analysis before you can say, yes I think it's OK it upsets the relationship. I definitely have the feeling that that would happen, and so you could say it was further difficulty. OK long answer on that one.

Q6

46 MV: 6. Does the degree of experience of individuals play an important role on the evolution of the process ?

47 SP: Yes, terrifically. I mean we only really in engineering use sums to substitute for experience. I think. If we had lots and lots - 30 years of experience - we would hardly do sums. And of course it is not just on specific things like the size of steel girders.

48 MV: So you say it does effect the evolution it just gets slow. You also implied that the slow process of getting to know your fellow designers and the difficulty in cultivating this trust and exchange with the architect, because as you say to the architect I have to go away for a fortnight and think then

49 SP: He thinks, what kind of engineer is this?

50 SP: He doesn't know that he has asked a really difficult question which no engineer could answer quickly or he may, if he knows the engineer really well and he's worked with him for years and then he asks the question the engineer then says I am going to have to think about that for a fortnight then because it is a previous experience in relationship the architect knows he has asked too many difficult questions. But if it is the first job they have done together, it's what kind of buffoon is this?

trusting
people one
knows

confident
engineers

The other thing is in the evolution of the process. Well in the evolution of the design anyhow, there is a lot which really needs to be done on hunch and feelings on how..... We think if we start to do it this way I think we shall get into difficulty with that sort of thing, I'm not sure what the things are but I have a strong feeling that is going to be a difficult way to move and those hunches are terrifically important and need to be really followed and you need to be able to talk about your hunches between the architect and engineers so you have to understand each other's hunches.

The architect has to be able to say, well are you really sure about that, I'm not sure what the problems are going to be, then we say OK let's have a look at it but all that which is not based on fact in the exchange of sizes in bits of concrete or steel or so but is based on a sort of feeling about how you are doing it, is really tricky and important that there is a good relationship between the two and is terrifically important on anything unconventional because you don't know which way it is developing. What is the form of this thing and so on.

51 MV: It sounds as if it is more important to be lucky enough to have the right chemistry than to have the right knowledge to participate

52 SP: Yes, maybe. I think that's right although you could take that argument to say it's more important that the engineer's heart is in the right place than he is actually able to do clever structural analysis and I don't think that is the right conclusion, I don't think there is any substitute for being a good engineer as an engineer. First of all you must be good at the job and then your heart has to be in the right place. There are lots of very good engineers I have come across whose hearts weren't in the right place, they just thought what a stupid idea and couldn't really get involved with it, whatever it was, and didn't have enough affection for the architect to try and explore what this stupid idea really meant and how you could get something that was satisfactory to everyone out of it. But I don't think it is any good the engineer having a real absorbing passion for architecture but not actually being crisp at engineering when the engineering has to be absolutely first class. I am sure Mark Whitby will say that.

the
engineer's
heart has to
be in the
right place

Q7

53 MV: 7. How does the different degree of familiarity that individuals have with means of communication and simulation affect the process itself?

54 SP: Do you mean computers and things?

55 MV: I mean physical modelling, computers, discussions, sketches anything that could communicate and simulate ideas.

56 SP: Where the process is designing the unconventional building, is it?

57 MV: That's right, yes.

58 SP: It hasn't with me or with us, I don't think that is has never been a case in which the different degrees of familiarity of individuals with the means of communication has affected the process - I don't think so. We are not at the moment anyhow in the world of computer simulations and things like that and I suppose most of the architects that we (just dealing with technical things) draw just about everything now on computers and so do most of the architects that we deal with and we communicate regularly with floppy discs and things backwards and forwards. All that is quite standard but when it comes to actually trying to discuss the design it is much more likely to use a roll of 10 inch paper or something like that, scribbles and hand drawn things. I don't think I know many architects who do proper design with a capital D on the computer - they do it by hand and then turn to the computer later on for the production.

traditional
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communicati
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59 SP: We have found that too in three dimensional structures. We haven't done the sort of three dimensional structures you were talking about - we may have done one or two little things but nothing like this sort of stuff but when we come across, it's quite interesting actually, because I didn't think of that at all, but when we come across this sort of problem of how is this thing going to work when it is three dimensions, we make models out of card or balsa wood or plastic or something to find out.

There is a model next door which I'll show you presently of a roof, which is perfectly straight forward in a way, but it has a very interesting three dimensional aspect to it and we weren't sure whether the sizes of all the members that we were talking about were right or too big. It comes back to the thing I was talking about before, the feel of the thing.

We hadn't done it like that, nobody had done anything like that before - we didn't quite know what these things would feel like and the architect said are you quite sure these tubes can't be smaller? and I said, well I think they can be a size smaller but are you sure they need to be, I think they look right as they are and I think if we make them much smaller we are really going to have to sweat blood over the sums to try and prove it. So I'm not quite sure. So we made a 3d model at 1 - 20 or something of the whole thing and said look this is what it looks like. He said oh yes, fine, let's use the tube sizes that we were going to use and it all came out wonderfully.

60 SP: We have actually done a little bit of 3d drawing with the computer from time to time but I just don't find it a bit convincing, it doesn't help me a bit, but I have no doubt that if I was trying to do something like Schlumberger, I would probably feel that maybe a 3d drawing would be helpful.

61 MV: Because you would be surprised to see that people like Buro Happold or Frei Otto and so on start off with a physical model and they even test structurally the model they can define the different curves, they have the experience of looking at the curve that is generated like say some masts that push it up and lift it and then they can play with the masts to find the right curve until it firstly pleases the eye and secondly works, it is the Victorian house in this case.

They look at it - when I was watching them - I saw them on a couple of occasions while they were playing around with the model and they asked me to produce these two masts that would lift up the tights and I had to come up with an idea which wouldn't tear the whole thing apart. And at the same time we would have a hole and another plane here where this mast would change according to the different heights we would like to test on. So I would have a sort of bolt here with a screw and holes in the masts. I couldn't understand why they were saying 'do this or that' but of course they know how to estimate wind uplifts and snow loads and so on on a model.

62 SP: We got involved with something rather like that where we were going to do some little tented covers for a market in London with Richard McCormac and I said I think we ought to get some tights actually and try pushing it around and see what it looks like so that we can get a feel of it. But I have not done this before, so it would take me a long time to acquire Buro Happold's experience of this sort of thing. I think that obviously would make a difference on a thing of the size you are talking about, your aviary and so on.

63 SP: The Mannheim Garden Centre, yes.

64 MV: That's very impressive, have you ever seen it?

65 SP: I've only seen photographs of it.

66 MV: It is still alive - they had anticipated, I think, 20 years of life and it is still fine, it stands up. It is quite touching actually, I went both times with engineers and designers and my supervisor and you can see how they look at it like a child, they look at it with real pride, because they know about it. There are stories behind it how stressful the situation was and they were all scared it was going to fall down and there were lots and lots of tests and they couldn't find somebody who would undertake the job and take the responsibility to say yes it's fine. Because they hadn't done such a thing before. So that is I think in the real sense what innovation is about. I mean that is a really innovative building.

67 SP: I think that was a fantastically interesting thing done, I can't remember when it was - it must have been 30 years ago.

68 MV: No, no - 17 I think. About 76 or 77.

69 SP: Wasn't it done as Arup. Yes it was before Happold left. I think what you said the person going to look at their building as if it was their baby. For anything that you have really put effort into, whatever, and you think it has come out well, I think you feel like that. Just one or two of the buildings that I have done, I have gone back to look at from time to time and thought this is the one!

70 MV: 8. Is it important that construction details and choice of materials have to be resolved at an early stage?

71 MV: That was with reference to unconventional structures.

Q8

72 SP: I think the answer is, yes it is. I think in almost any building however conventional or unconventional, it is important that the choice of materials and construction details are there. I mean there is a definite feeling in some schools of architecture that you start off with great concept and in due course you have to work out how that is going to get created, and in some places it is even thought that somebody else can sort that out.

choice of
material and
materiality
thought out
at early stage

73 MV: Pass the buck.

74 SP: I think that that is completely wrong and that the materials and the construction are inherent in the design, absolutely in it and I think it is funny in way that the other idea can take hold at all - and it seems to me that it has taken hold without anyone realising that it is definitely completely different from how all the great buildings of the past must have been achieved.

I mean the Italian Renaissance architects didn't start off thinking I am going to make this fantastic shape, I wonder what I am going to make it out of. They knew exactly what they were going to make it out of and they knew the known properties of a material and in the case of Brunelleschi and the vault, he knew he was going to have to stretch everything and do it in a different way, but I mean the whole essence was using a certain range of materials to produce a wonderful, enchanting, exciting thing, not the wonderful exciting thing is a thing on its own and the materials rather spoiling the idea but sometimes if you can't get the engineer to do it right and I think that is absolutely appalling, that as an idea. So I think yes, absolutely.

approximations
are
allowed in
small scale
buildings

I should think that everything is increased by the scale of what you are suggesting here really so that I mean you can get some distance without being absolutely clear about it and if you are only talking about spans of kind of 10 metres or something you can fudge things, like anything, if you have to. Whereas with spans of 100 metres you can't at all - it is unfudgeable. In fact I have seen that actually happen. This point came out in - I can't remember where it was now - I did a little bit of teaching at one of the London Schools of Architecture and they were doing a footbridge project and they all came up with ideas on how to create a footbridge or how a footbridge should be without any reference to how it should be constructed.

It was quite extraordinary, sort of breathtaking in a way, because it is not just a question of this is inadvisable and you won't be able to build a very beautiful foot bridge like this it is just that these ideas are totally irrelevant and have no possible future at all. You might as well say I think it would be fun to make this 500 metre span footbridge entirely out of old stilton or something. It is simply not an interesting thought. Do you see what I mean?

And I had quite a lot of difficulty in getting that over in a sort of polite and positive way to students who had obviously thought quite a lot and had come up with an idea, that actually bridges are very largely the result of how you actually build it. I mean Calatrava is sort of bucking it a bit and anyhow we have all sorts of techniques for doing things now which allow us to do all sorts of things....

75 MV: Well he has a knowledge of both architecture and engineering that's a different case altogether.

76 MV: 9. How significant is it for the process to learn from other people's mistakes and previous experience?

experience

77 SP: I think experience is the most important thing.

78 MV: 9. Are commitment, determination and enthusiasm necessary for innovation?

enthusiasm is necessary for any kind of building

79 SP: Absolutely, totally. But I suppose going back and asking the other question, are they not necessary therefore for conventional stuff. The thing that is produced gathers up, encapsulates or something like that the commitment, determination and enthusiasm of the designers and if there hasn't been any it's jolly transparent actually. It's very obvious. I don't know what you can actually do by looking at buildings, but one of the reasons why spec. office blocks are on the whole so disgusting is because you can see that there wasn't any enthusiasm, it wasn't produced with the purpose of enthusiasm, it's just space.

80 MV: But also I think the determination or the commitment refer to the unknown situation.

81 SP: Well then of course in all sorts of construction but usually in unusual situations you suddenly find something happens, maybe really late, I mean when the builders are building it and then you have to think of a way out of it or presumably a way around it, or a way of dealing with it anyhow which presumably people like to think of. I mean the Sydney Opera House. There was a long stage before the Sydney Opera House, somebody else came up with the idea of cutting it out of bits of orange peel, sort of thing and it stopped being a shell and Ronald Jenkins stopped getting interested in things.

There was quite a long stage before the orange peel came up and everyone thought that's the way we can do it, because this makes the geometry comprehensible and so on. It is one of the worrying things about tents actually - I know I like some tents and I know I don't like a lot of tents and there is something, I have a feeling that I myself like very well developed simple things.

The Sydney Opera House, I don't understand its geometry, I have had it explained to me how it has all been worked out and underneath that is something very, very simple, the curves. In the same way that probably, if I understood it properly underneath Corbusier's buildings there was a very simple theory of proportion and that a lot of classical buildings there is quite a simple theory of proportion and that in the great cathedrals the whole thing is built as a modular thing. Have you heard Jacques Heyman talk about this?

82 MV: No.

83 SP: Well this is an absolutely wonderful lecture which he gives from time to time. He was Professor of Engineering at Cambridge until fairly recently and he has done a lot of work on stone structures and arches and things, and he explains very, very clearly, which I suppose everyone knows and so on that of course in the 12th century they didn't have steel tapes with lots of little divisions, the master mason had a length of something which was the measure and so you can't say I would like this to be about 1.16 metres or something, because that doesn't exist as a concept actually.

84 MV: Mathematics.

85 SP: Yes, but very, very simple mathematics when the cogs are ten of these things apart and the straight sharp is 15 up the point..... and so on and the radius of the Gothic arch is something else and they all relate to this single dimension. So that underneath a complicated, really rich piece of structure there is a very simple thing and I think is absolutely wonderful and it is one of the most satisfying ways of building something that if you know completely how it is going to happen once you have developed this simple thing, it all follows you see and I don't think that tents as developed with tights and computers and things quite often have that simplicity. Sometimes they do. The Schlumberger doesn't have any simplicity at all, it's a very complicated

86 SP: I suppose really I should try to analyse the ones I like and don't like and try and see what it is. I think for instance the tents at Lords seem to me quite good. I quite like the tents at Lords and I don't like Schlumberger at all. I think the Glyndebourne ones are a bit silly really. This one here at 'Imagination' seems a bit silly, in fact it's more that , it's definitely wrong somehow.

87 MV: The tricky thing about tents is that there are other ways, simpler and purer, clearer ways to go about the same problem solving task for such a long span, or not such a long span. Regarding 'Imagination' they could easily have had a truss and some glazed panels on top, but then they claim that having flexible material because the two buildings weren't parallel it would make things easier which for that span to be covered and so on, so they talked about this problem and made the tents serve the purpose more effectively than any other structure.

88 SP: I went long before the tent started its new life, so to speak with Aalto, I was working with Ove Arup & Partners on the idea that the British Council would have a tent which it would take round to different countries in the world and put it up.

89 MV: Like a marquee.

90 SP: Like a marquee, and then you would do British ballet or music in it and then you fold it up and take it away.

91 MV: Like a circus.

92 SP: Exactly like a circus and it was going to be really super-duper bit of high tech.

93 SP: and could we invent a brilliant way of doing it. I was doing this with Peter Rice, who I worked for at that time and Ted Happold and while we were working on this thing, the architect was Theo Crosby, Ted and Peter decided they would go and look at the big tent being put up at Battersea for some Battersea thing and they went down there and watched the chaps put up the circus tents, effectively, and they came back rather quiet and crestfallen because half a dozen men had put up this enormous tent with entirely conventional methods, bits of wood and a few pins driven into the ground and some winches hand worked, the whole thing went up just like that and they thought all this clever stuff with hydraulic jacks and things, it's not going to be as good as the old, old thing which has been developed over the decades.

94 MV: Well they had this similar example of the

95 MV: 11. Which comes first unconventional structures requiring close collaboration between engineers and architects, or close co-operation between engineers and architects producing unconventional structures?

96 SP: Ahh, I don't know. I have already said that I think close collaboration with the architects and engineers for anything of serious architectural interest is necessary anyhow but whether the close co-operation between architects and engineers produces unconventional structures or you could only produce unconventional structures by already having close co-operation. I wouldn't have thought historically that was right.

I would have thought that architects thought of unconventional things without already having a close co-operation with those engineers. I think it would be far better if the thing were developed in close co-operation but I don't know that it is actually..... The first part suggests that you only get a thoroughly interesting unconventional structure because of close co-operation and I don't think that can be right, can it?

97 SP: I don't know, how well did Peter Rice know the Spanish architect to build that mad wall.

98 SP: It was a real pity at Sydney Opera for example - actually I'm not sure. I was going to say it's a real pity that they did fall out and that more things didn't come out of that but actually, Utzon, I think, is such a wonderful architect in totally conventional stuff. I mean his little houses in Denmark I think are absolutely marvellous buildings,

99 SP: so I don't think he had to go on doing Sydney Opera House at all really, but...

100 MV: But that is what made him well known though...

101 SP: I don't know what he has done since. I don't know what has happened to Utzon, do you know, is he alive?

102 MV: I've heard about him. He must be, because we would know about it. When I started the research someone said why don't you call Utzon, but because I travelled all over the place to find the rest of the people, it was a matter of resources, time and money. Besides I think even nowadays to him, this is a very touchy subject to talk about. In the previous phase of the research I had put down very personal questions about group dynamics and how people felt about their fellow designers.

103 SP: Is he in Denmark?

104 MV: I heard that after Sydney Opera he did a governmental building, Parliament or something like that. It was quite extraordinary on the plans but it wasn't as complex as the Sydney Opera House. But as you say, most of his stuff is not unconventional. It was just an idea and I heard when people talked about it that he had such a daring idea he put forward simply because he believed he wasn't going to win the competition.

105 SP: Whether he was pleased that he got it, or not. You could ask Sandy Wilson whether he's pleased.

106 MV: I have talked to Ted Happold and Charlie Wymer.

107 SP: What before he had his bike accident? That was terribly sad because he was going to do fantastic things to education.

108 MV: He was a very close friend of my supervisor's.

109 SP: He had a fantastic amount of life in him really - very, very sad.

110 MV: 12. Do you think that current educational practice equips architects and engineers to work together?

111 SP: I think that is easy. Absolutely not. I think architects are fairly badly educated in quite a lot of respects and engineers are appallingly educated. Really very badly educated.

112 MV: Are you talking about education in isolation or are you talking about... Because the question refers to the cultivation for collaboration.

113 SP: Yes, and I think quite specifically the failure of the engineers education - let's start with engineers' education to start with. The engineers' education is bad in particular with the things that would help him to work more closely with the architect. In quite a lot of Schools of Engineering in this country design is not taught at all, it doesn't even come into anyone's head.

It's analysis - and you certainly have to understand analysis, you have to be very good at analysis but the whole function, the purpose of analysis is to analyse something which you have invented to design and most of the people who teach engineering don't know anything about design. They just don't know how it's done or what really counts or what the process is like and it is a very different process from analysis. Totally different and there is no.....

Q12

education

architects'
and
engineers'
education

If we were trying to equip architects and engineers to work closely together we would also attack the very considerable cultural differences between architects and engineers and we would say to engineers you can't get your degree until you have written several essays on Beethoven's string quartets and done two terms worth of life drawing and this and this. Because you are not just going to sit there in gum boots doing sums, you have actually to get out, you know.....

114 SP: There is a total failure there. I have just been through this very vividly, because my son went to Cambridge and read engineering, like I did and came out with a first class understanding of analysis and extreme irritation that he had not been taught anything about design. I didn't think about it at all, I then thought right at the end, I wonder what I want to do, but Oliver was more clear about what he was interested in that he felt that it was terribly dry so having finished his degree course he thought what should he do and he decided to go to the Royal College of Art and he did industrial design engineering for two years which got him straight into - after a couple of weeks he said last week we were trying to draw, looking out of the windows of the RCA onto Hyde Park, the spaces between the things that we see.

Which is an interesting idea, rather than tree here and there and then there was a lot of life drawing and then there was stuff about moulding and printing and all the different ways of making things and making models yourself all the time with your own hands. Quite unheard of in most Schools of Engineering. I think that really brought him out, he developed the whole piece which I didn't know was really there at all and if he hadn't done that I wouldn't have understood quite what the potential was inside him. Well now that is exactly what we are talking about. That potential is mostly not developed in most engineers.

115 MV: No it is not apart from Cambridge as a postgraduate course which is a masters.

116 SP: Leeds is quite interesting actually. We have two engineers here who were at Leeds. They both did four years and the third year was in America in a School of Architecture or Engineering or whatever and they know a lot more about how things are put together but I'm not really talking about that. I think what we are trying to deal with, because there are efforts being made to make architects and engineers understand each other better - and I have been doing some teaching on a thing called IDBE which stands for Inter Disciplinary Design for the Built Environment which is a course which is running at Cambridge for people who have done Robin Spence's course.

117 SP: That is trying to make people understand each other better, but I don't think I am really talking about that. I am talking about much more fundamental things because I recognise somehow or other all this stuff that I have given you about the inherent nature of the thing you are trying to develop has come out of starting one particular experience for me in Ove Arup & Partners a long, long time ago and after that experience I was doing what all engineers do which is take the architect's drawings do some sums and think about and then we had a building to design which I still think is one of the ones that I would go back as my baby sort of thing, I don't actually enormously admire the architecture of it, but the idea in that building was really, really interesting.

118 SP: It's the Civic Centre of Sunderland, it's based entirely on a triangular grid and it gives you a new thought, what does that mean a triangular grid? - and we developed with the architects a way of making this building and while we were doing it - and to start off with I thought well, the economic way of doing something is to span this like and span that like that sort of following my nose and then in a series of discussions with people particularly, I think with some help from Mark Kitchen, who is one of Michael Barclay's partners, runs their office in Norwich and is a very, very good engineer, I suddenly realised that this wasn't how you did this particular building - what is this building trying to be, how is it going to work and it didn't start life on a triangular grid - it started life as a building consisting of one, two, three, four, five, six.

What the architect sketched as an idea was a figure of eight in which these sides which were 120 degrees and there was a courtyard in the middle and this is the building going around it and sometimes the building is this wide with probably a line of columns down the middle and offices on either side and there could be a corridor against that and sometimes the building has, and sometimes the building was this wide with two corridors and in the middle you would have, for instance the services and staircases and things like that and deep straw and flitting around this, I suddenly thought what we need is a triangular grid and it had an absolute logic about the geometry and if this is done with flat slabs you don't put columns on the corner you put columns in because the flat concrete has to grip the column.

So there is a sort of principle of how you make something. So that column is there and this column has to be there so you have a grid there, there and there and then I worked up the grid pattern so that that would be the thin bit of building which has the one corridor and the columns like that and this one has to be in the corner and you turn that corner, right? and the wider bit you have another bay of that, so here you have column etc.etc.etc.....

119 SP: I said if we do it like this we could get a system which would work and I suggested a complete replan of the whole thing which had hardly been done because we were all working close together in the same office like Arup Associates and it was the first thing we worked together on properly. So they hadn't got committed to it, they weren't offices of particular sizes it simply said Borough Engineers Department, Architects Department around here etc.

120 SP: So the whole building was replanned, quite a small change a metre here and there to fit onto this grid and it went ca-chunck onto the grid and then I thought this is actually a little example of what the engineer is supposed to do, you suddenly see something in the architect's mind which hadn't been in your mind. The whole thing is based on geometry it suddenly becomes simple and it became completely simple, we knew exactly how we were going to do the whole thing.

121 MV: I think what you said is related to the last question.

122 MV: 13. Is the borderline between the skills and roles of architects and those of engineers appropriate for the design of unconventional structures?

123 SP: Yes. I don't know the borderline? Is it appropriate to have a distinction between the two, no, obviously..... There must be more overlap, as you said in your tents, the engineer can actually say it will have to be like this, if you want that sort of thing it will have to be this sort of thing and so the normal borderline where the architect says that is what I want and the engineer says, well I can almost do it and the architect says, oh, all right then, that has changed because the engineers come right over it.

overlapping
of disciplines

I think going back to your original question no 2, but is that true of other buildings, then it is all to do I don't think it is really to do with size, I think it to do with how determined you are to get the right answer in capital letters because in order to give the right answer you can't have anyone saying that is what I want and the other person saying I can't quite do it and sort of resentment. You actually have to work to get everyone feeling that they have got it right.

rightness and
proper
relationship
of things

If the engineer says it is right, meaning it's big enough and it will stand up, and the architect says it is right, meaning, I like it - that isn't good enough. Rightness is more than that rightness is a proper relationship of all these things. Your general thesis that the unconventional buildings to the sort of scale that you are talking about make all these things absolutely crucial and highlight them must be right musn't it?

124 MV: That's what I think. It has been the whole has to be proved. But I think the borderline refers to skills and roles, you see. Perhaps it is a quite traditional way of defining a design team but if you look at flow charts of the design process of the given building or if you look at global models of the design process the architect is supposed to do (a) the engineers to do (b), (b) will follow (a) and so on - so that is a kind of established borderline. And now the question is trying to ask whether this line is dropped when these structures are designed.

125 SP: I think I have never got to a point where the sort of structural imperative was so great, as your example of the tents, having to be like this, that there couldn't be a discussion about it. I have come across jobs where it was really exceedingly important from every point of view that this structure should be in a certain way, but that probably we could have thought of a way around it if somebody said no, you can't do that. I worked for ten years in Arup Associates when it was the truly multi professional groups. It was a very interesting experience and it is right on your subject actually. Arup Associates has never done any of this sort of unconventional architecture.

126 SP: But the idea was that the architects and engineers would all work really closely together in a truly multi professional group and so Arup Associates was organised in groups of about 20 people, not more. Say you would have four architects, two structural engineers, two heating engineers, electrical engineer, plumbing engineer, three quantity surveyors, building surveyor and administrator as a group.

They all worked in one open plan space and they all worked absolutely together and they didn't work on anything that wasn't all together and it is extremely difficult to do that to a program because at the beginning everyone ought to be involved and then there is a spell when the engineers have got to get details done, the architect is still, perhaps, thinking about windows. The work goes in waves.

unusual
ways of
operating.

It is a very interesting idea because you cut across all sorts of things. One of the things that if you want to get ahead you should be in charge of an office where people work for you - if you are going to work in a group it was recognised that it was essential that all members knew and understood each other and worked closely together, so it has to be as small as possible. So there is no hierarchy in the group.

We had no draftsmen at all which for architects is not unusual but for engineers is very unusual. Engineers did their own drawings. So if you had two engineers in a group, they did all the drawings themselves and so you had to be interested in working like that and sort of foregoing any visible form of status. You had no glass office with a rubber plant and a girl with long red fingernails outside.

127 SP: And sometimes it worked fantastically well and we all understood each other but if we didn't agree with each other the process it could be enormously painful and there was a stage, for instance in the development of one building which came up just at the point when the oil crisis, in the early 70s, before you were born anyhow, we all started thinking seriously about the energy use and stuff and the architect hadn't been in the group very long and he came up with a design on this big site, lots of fresh air, no pollution or noise of any sort of a beautiful pristine sealed office block. The heating and structural engineer who had always been left wing about this sort of things, said there is an energy problem coming up. What about natural ventilation?

128 SP: We could not resolve things actually. There was a huge battle about it and then he said OK you try and draw it yourself. One of the structural engineers tried to draw something - he did the best he could - and the architect said this won't work because of this, this and this and there was a real row and the row ended with that architect being asked to leave and a different architect coming in and he designed quite a good building which two open courtyards and a thin building with opening windows.

So that in that particular example the actual technologists triumphed if you want to put it like that. It was a total failure although we had every possible help in trying to work together because we were all in the same space, had lunch together etc. etc. - really tried to make something - but it still didn't work because we couldn't get the agreement about the line of approach. But the idea of Arup Associates was absolutely fantastic, when it worked well it worked immensely well, so smooth.

Peter Foggot from one of the Arup Associates groups designed all that Broadgate stuff with fifteen people. SOM had offices of 70 or 80 or something to do the same sort of sized work or whatever it was. It was enormously efficient and not just efficient but very effective. They knew what they were doing and they all wanted to do the same thing, they understood each other, they had done it before. That was enormously effective in many cases in designing quite conventional structures and I think is really crucial to the effective design of good conventional structures.

Actually the buildings that came out of Arup Associates, some of them I think are really fine pieces of architecture and some of them are not - they are just good - never bad - but I think some of it was really nice stuff but none of it was unconventional and I don't believe that Arup Associates would have found it easy to design the TUC building somehow. I have wondered about that, whether that is to do with the fact that the proximity of all the engineers and surveyors somehow restrained the architects.

129 MV: I think we have covered all the questions.

130 SP: I still really don't know whether there eventually ought to be actually just somebody called a building designer or whether we all ought to be divided up into different things.

building
designer

131 MV: Well I think the reason why this new role is quite fashionable and crucial in buildings is because somebody who really tends to be the architect in most cases, or architects like to think this way, that they are going to be the projects managers.

132 SP: But they seldom are, are they?

133 MV: That's right but I think that is the idea of understanding and appreciating the different roles and different disciplines and their importance and.....

134 SP: Calatrava is a very interesting example because the engineering is very silly, he is not really a very good engineer. He can work out, but the things he wants to do were a bit daft really, willful silly, and all the same too.

135 MV: I think it's the confidence that he has the knowledge, he is not relying on anybody.

136 SP: No. But he is an example of one person who can do it all himself and I don't know if we would be better off if we gave up the idea of having architects and engineers as separate sorts of animals we should now develop the idea of having building designers who design the whole thing.

137 MV: I think it is a question of education of how long one should afford in terms of the time.

138 SP: Oh yes - that is a really big question. I have gone on a lot about experience which I really think is the crucial stuff.

139 MV: Go onto a second school in a way?

140 SP: And I think architects spend too long in school myself.

141 MV: But I think the architectural education is much longer than that of the engineers because it takes a long time, not to get deep into things because I don't think that the architects get the opportunity throughout the study to learn things in depth, but they do spend a lot of time understanding the different factors of importance to the design and that is perhaps why the engineers are not taught design because it is such a diverse subject, because we do environmental studies, psychology of space, construction and structures. So I think the five years is because there is such a wide range of things to learn, even on the surface, if you touch upon the surface you need time to do that. Where I think that the engineers are more fortunate because they are focused.

142 SP: But the way to know how to do something is actually to do it. Which is one of the most outstanding examples of rage caused by not having that, like the people from English Heritage who come and tell you whether you can or can't do something. You feel that most of them haven't really tried really working themselves in complete detail with an old building so they understand what it feels like, what is going on, how is it actually put together and so on.

Of course I'm not really involved in this very much because the engineer doesn't usually get involved in discussions with English Heritage but I have actually witnessed and been part of conversations, in which an architect who knows absolutely all about old buildings, is being told by someone from English Heritage that he can't do something and we have subsequently found that the floor..... and the architect said I'm sure you will find this floor is not original and not important etc. etc. English Heritage say we must keep it and then we have lifted the floor boards and find that the floor joists are five years old.

143 SP: If you are sensitive to it it you can think, is there actually something inside this or is it just simply a pretty shell or an unpretty shell or whatever and that is the same thing as going into an old building and thinking, this doesn't feel right. Somebody's done something in here, I don't know what,. they may have done it quite well but I don't think this is how it should have been once upon a time and so on and you don't just learn that by going through the books - you go through hundreds of buildings and then you just get it. So I'm tremendously in favour of experience being the basis for everything and of course the interrelation between the architects and engineers.

144 MV: That's not so easy for us young people.

Interview with Mark Whitby

1 MV: So you have seen from the letter I sent you what I define as unconventional structures.

2 MW: What do you mean, I've just read it, reiterate.

3 MV: This is the title, the definition I gave and that is a very broad one in order to cover many structural types. The buildings below are the buildings I explored.

4 MW: Right I can see the unconventional structures as long span covering column free spaces, without employing beam column structural systems. So that is quite straightforward.

5 MV: 1. Do you think that the dual architectural and engineering Q1 nature of unconventional structures influences the design process itself?

6 MW: They arrive out of the desire for clients to have solutions. Each one of these buildings that you have listed here are as a result of clients wanting solutions which are unusual in their own right, whether it's the Mannheim Garden Centre.....

7 MV: How do you feel about your own experiences, is it just the client or could it be the designer first.....

8 MW: They present an opportunity for the certain combinations of people to feel if you might say, there is a tendency for everyone to look for the unconventional opportunity and to make the most of it because life can be very boring otherwise. So yes it is natural to want to make things extraordinary for some people. Other people would run a mile from it and they would make it into something different and a lot of opportunities are missed purely for the sake of trying so that there are cases where clients might have very inspirational ideas but lose them when they give them to the wrong people to carry out those ideas.

9 MV: Do you think that influences the process though?

10 MW: The process?

11 MV: Yes, having this dual nature of being architectural engineering. Q2

12 MW: I don't think it necessarily influences the process. It's not the fact that they have a dual nature, they are just opportunities. Either person working on their own or apart could seize the opportunity. Where it does influence people is when one person feeds off the other so you may get an engineer encouraging an architect to do things which are outrageous and vice versa.

13 MW: You could get the architect who is encouraging the engineer to test his skills and prove his prowess. So there is no doubt that there is a bit of that going on.

14 MV: 2. Do you think that the architectural language of unconventional forms is different from that of conventional and that influences the process?

15 MW: All the ones you talked about are quite different but there are quite a lot of ordinary unconventional.

16 MV: You don't have to specify with regard to the buildings that are listed there. It is about the general viewpoint regarding the design process of any unconventional structure. You don't have to speak about the buildings that are listed.

17 MW: I don't think this is true. Obviously is an unconventional form different, we are not used to them, they are not ordinary functional objects but there is not necessarily an architectural language, this really just comes from the desire for people to solve problems in a different way and that is where they come from. It really is just a human desire that exists among some people to try and solve problems without preconceptions. Preconceptions make us do what has been done before which is what conventional form is all about.

They are conventional because they are preconceived and it is obvious what the answer is. Sometimes it's obvious what the answer is so that you don't even think about and in unconventional forms they arrive from people not accepting the preconceptions. I have worked on bridges for instance where there have been preconceived ideas of what a bridge should be like and yet the problem was solved by a totally different way and that produced something which was a span of less and gave a form which was quite different and yet answered the brief and yet the other people had been thinking of cable stayed or arch or whatever - they were just full of these preconceptions.

Unconventional form comes out of not having preconceptions and letting the problem tell you the answer as opposed to the answer coming from some preconceived idea of what was right. If anything the architectural form is a hindrance to the idea of making unconventional structures because it is a preconception in its own right.

18 MV: So you are questioning the title of unconventional, aren't you?

19 MW: Well not really - unconventional form is something which is not normal and therefore obviously a solution is going to arrive as a result of desire and that desire to think about something in a unique way as opposed to just solving the problem. Most designs are directly done according to rote and are often tremendous lost opportunities. That applies right the way through to even small projects, tiny projects.

22 MV: 3. Is there a stronger interrelation and interdependence of architectural and engineering considerations when unconventional structures are designed? Q3

23 MW: Yes, because clearly you don't get one without the other - if you are working on an architectural engineering problem it is only as a result of suggesting that you can do something in a way an alternative way, that you can come up with an idea which is unconventional. You have to have a culture in which this works so when you are working together with architects, they challenge the conventional and they try and prevent it by placing blocks on conventional thinking.

The architects are therefore encouraging unconventional thinking and often it is the engineer who is providing ideas, the solutions to a problem and the architect, all he is doing is marshalling, rather like a conductor conducting music. Very good architects are people who start with blank pieces of paper when they are having conversations and things grow out of those pieces of paper. Other architects have all their ideas in advance.

24 MV: Could one argue that the same could happen for any structure and there isn't.....

25 MW: Oh, yes, any structure. There are always opportunities with any construction for unconventional solutions. Whether it's a staircase or whether its a way of treating a roof light. It is possible at any stage in any program, whether it's a house, or house conversion anything for it to be unconventional and whether it's in unconventional structures or unconventional appearances.....

26 MV: Do you believe that there are people nowadays who work in a traditional way of having no interaction between the different disciplines.

27 MW: Oh, yes there are plenty, the majority of buildings are built by people who think the design is the object carried out by an architect and structure is something that is a fitting out process and in the U.S. it is believed that architects decorate frameworks. It's broken down to that. Wherever you are in Europe you see the tremendous division between the disciplines and people don't break out of certain moulds. Because the engineer doesn't assist the architect with the design and demands much better information before he will even start his work.

28 MV: Because some people I talked to don't believe that there isn't such a thing any longer but that always architects and engineers work together regardless of the nature.....

30 MW: It's very rare in many respects that you get good buildings. What you see published is one tenth of the top of the iceberg, the rest of it is just under water and it's what we think of ordinary boring stuff which is functional and does the job but not anything special.

31 MV: 4. Is there a necessity for simultaneous and equal involvement of architects and engineers from day one for unconventional structures? Is this more necessary than for conventional structures?

32 MW: It is quite interesting because I am about to give a lecture on a couple of houses we have designed for architects and it's interesting because every time that has happened and architects come to us with a design which is almost complete and in many cases our achievement has been to make that dream real and they have been very near to dreams - on the edge of reality and our skill is to almost to make their dream real and they get great pleasure from that, particularly when they go away and say they did it all on their own.

When we do a bridge for instance, we don't necessarily have an architect in terms of thinking about the idea, they come along later and help us mould it to the final form. So it is quite different. They need a certain knowledge in a design sense which is quite well achieved as engineers because we have a sense of what good design is and we know. Architects have a similar sense of structure. The problem with architects is they haven't got the confidence or knowledge to make the structures work.

33 MV: What the question is asking is whether you feel that in the case of unconventional structures.....

34 MW: No. I am thinking about a little steel frame that perch over a ravine. No question about it the architect had the lovely idea, a dream and the engineer made it work.

35 MV: They can't do without you.

36 MW: No they can't do without us. They have to go to somebody who shares the dream and is prepared to put the effort in to make it work. Because what happens is you see architects' dreams which have been completely messed up by the wrong engineer. That is where it fails. People love to think these two people work together as one but they can be almost separate.

40 MW: The engineer has logic on his side when he is doing something and this is great power. You can say why we want things to be like they are but architects often have a great problem with saying the same. When we make a bridge we can actually describe it from a mathematical point of view but it is quite fun. So it is true that lack of technical knowledge does really hold back the process.

41 MV: 6. Does the degree of experience of individuals play an important role on the evolution of the process? Q6

42 MW: Yes. The older they get the less likely they are to do unconventional structures. But it's worth saying that it's people who pioneer ideas are less likely to get caught out by them than the people who follow along behind.

44 MV: But don't you see a contradiction between introducing innovation and having the experience and how can you get the two.....

45 MW: Yes, you could argue that but I think that it comes often from the thinking process and unconventional thinking process, someone who will listen to an architect sort of desire not to do something in a certain way and therefore develop a different approach so I don't think youth is necessarily a hindrance to innovation. In many respects you could argue that a lot of innovation may come from a naivety which is born from a certain youthfulness and I have seen quite elderly statesmen in terms of engineering come up with the most awful ideas because they believe there was a way of doing it which happens to be their particular bent.

49 MV: Can I explain that communication is in relation to physical modelling, discussions, sketching, computers...

50 MW: Well the first thing is that if a person can't draw his ideas then I would argue that he is hindered. If he can't think an idea through in a traditional manner he is hampered. The truth is that you cannot suggest anything as an engineer that you don't yourself know you can make work.

Now you may not physically be able to do every single step in the process but you have to know what the steps are and you have to be able to criticise every single one, because when you suggest ideas which are beyond your capability it can be guaranteed they are going to fall apart on you. Because you can't judge how other people are managing them.

51 MV: I think I have to give you a clue here about this question. Think of the use of three dimensional physical models as in the case of unconventional buildings.

52 MW: Well we make models in this office of three dimensional objects and yes that way of thinking,

53 MV: You think that if it's straightforward then we don't need to do.

54 MW: You need to do it less on a straightforward building than you do on a unconventional one so..... If you know how to make models, how to go about it, yes that's true.

55 MV: 8. Is it important that construction details and choice of materials have to be resolved at an early stage?

56 MV: That again refers to unconventional structures.

57 MW: Well you don't know how you are going to build something whether it's conventional or unconventional. You might know who might build it, you don't know how and it is no good suggesting something that can't be realised. There are books full of those designs but they are no more than designs. The reality is if you want to make something you have to know how.

58 MV: Yes, that is why I have in the same question that material was again decided in the very early stage.

59 MW: Well obviously, things evolve but you have to have an idea of how you are going to do it and that idea will modify in time.

60 MV: In extreme cases.....

61 MW: You choose, you change your ideas. We do things and change our minds but one of the most important things about designing unconventional structures is to have the ability to change your mind and that is a trait that goes with that - you are flexible so you will evolve a solution as opposed to being rigid about it.

62 MV: What I am saying is that in the case of unconventionality, perhaps some materials are excluded right from the beginning, for example if you want to cover a long span you don't consider masonry as a materials.

63 MW: I've seen big bridges now of masonry. I think, be careful, don't ever rule anything out, nothing is excluded. There are all sorts of ways of making things and the unconventional concept of considering the unusual and you can do anything.

64 MV: Peter Rice has talked about it and he says that nowadays innovation with regard to the use of material is either using a conventional material in an unconventional way, or using an unconventional material in a conventional way.

65 MW: Well that is just a way of putting it. It is a big risk to combine to inventions on one occasion so you would be slightly foolhardy person to say well I am not only going to do something that is unconventional but I am going to use a brand new material. We are responsible people we work for clients and they pay us money, they don't commission building as our own personal experiment.

67 MV: 9. How significant is it for the process to learn from other people's mistakes and previous experience? Q9

68 MW: Absolutely essential. The whole of life is littered with disasters and it takes several experiences to see the process they have gone through and what goes wrong and yes I believe that all we are as a civilization is a sort of continuum and that continuum our lives are based on what we have learned from previous people's lives and they will learn from us.

69 MW: 10. Are commitment, determination and enthusiasm necessary for innovation? Q10

70 MW: Well, absolutely. I could say commitment..... You can't have an idea and not want to follow it through. You have to be determined because there are plenty of people in life who will tell you it's not worth doing and enthusiasm yes, because you have to get other people to believe in the idea in the first place so yes, they are the three ingredients that you have to identify and they are good words actually.

71 MV: I was given another one today which is rigour.

72 MW: Absolutely right. As an engineer you have to be rigorous. You have to want to make it work you have to be committed to see it through. So many people have not got the commitment to follow everything through. If you do something special you have to be thinking it in your sleep and I have woken up in the morning to discover that I have been thinking about the fact that I have got one tiny pin holding up a whole building and then have to make sure it's two.....

73 MV: 11. Which comes first unconventional structures requiring close collaboration between engineers and architects, or close co-operation between engineers and architects producing unconventional structures? Q11

74 MW: I think unconventional structures I would say because in a way, but it's difficult, you could argue they come from the people working together but equally they come from people working apart so neither is absolutely true.

They exist as part of the language and then someone has an opportunity to make them work. But neither of those things is necessarily true. They do require ultimately to make them happen - collaboration - they require the commitment of whoever is going to involved the architect or engineer. But there is no first or second. Everyone else might say that collaboration comes first but that is in an ideal world .

75 MV: 12. Do you think that current educational practice equip Q12
architects and engineers to work together?

79 MW: The truth is that engineers should be made to be engineers not to be made into architects because they are obviously going to have responsibilities that are different and if you start making architects into engineers or engineers into architects you suggest that they have a role that is different from that of being an engineer.

85 MW: It is very difficult for education..... Education is a process that people seem to see as isolated from work experience. The truth is in life your rate of learning increases with time. The more you know, the more you can understand, the more things make sense, the older and wiser you become and all that university education is, is a sort of booster. It is like the rocket that gets you up out of the gravitational pull of the earth. It is a means of getting you into a position whereby a lot of things may make sense if you are exposed to them.

Now a lot of people get that boost and then they always fall straight back to earth because they get into a very narrow field and they get pulled back down, they don't ever really get beyond that sphere of speciality that they are involved in. Whereas if you are lucky you can get up and you accumulated a lot of varied knowledge which is all associated with the core of knowledge that you were educated in and it could be that you learnt business and engineering or French and engineering or something and you can develop a complete character which comes from that education but the education will not make you an ultimately a different sort of person.

99 MW: 12. Does current educational practice equip architects and engineers to work together. Q12

100 MW: The best education an engineer can have is to become proud of himself being an engineer. They need to have courage in their own ability and then their professional standing. They have to know that what they have to sell is something of value and that is fine if you can do that.

101 MV: Is this in order to come to equal terms with the architect?

102 MW: The architects are taught in many respects how to be confident, presentation skills etc. Overconfidence in engineers means they can be blind to the weaknesses. I am all the time saying to engineers take care, if you think you have done it go away and look again. It is very, very dangerous to be overconfident in engineering. You have to be able to present your schemes with confidence but able to adopt the approach of challenging yourself and being challenged by others. Confidence is a front, a weakness sometimes.

106 MW: There is nothing that is depreciative about engineering education and the answer is there is nothing depreciative about architectural education - in terms of making the two overlap - what should happen is that engineers need more confidence in their own position as engineers.

I am a great believer in creative tension that actually exists between architects and engineers. That trying to make them the same is to almost get rid of that tension which is actually this thing that works between them. If anything the engineers just need to be cultivated in engineering.

110 MV: 13. Is the borderline between skills and roles of architects and those of engineers appropriate for the design of unconventional structures? Q13

111 MW: Engineers have to make it stand up. They have got a responsibility to make that thing work. The architects in a sense when it gets to unconventional is in a bit of cloud cuckoo land. He is actually at the mercy of the engineer's ability to make it come together.

112 MV: But as you said earlier you don't believe that the engineer has to learn about architecture or the architect has to learn about engineering.

113 MW: No but there has to be a mutual respect and provided that exists it's fine.

114 MV: But if it is respect regarding knowledge doesn't that imply that

115 MW: No you can't respect someone without understanding what they are about.

116 MW: How can you really respect an architect unless you.....

117 MV: How are they going to understand each other if they don't understand each other's knowledge.

118 MW: Experience, experience, experience. You don't come out of college equipped to go ahead and do something, you come out of college with a certain knowledge which gives you a kick start, it is how you apply that knowledge in time but you obviously have to come out with desires of what you are doing and there's certain luck that comes with it.